Life Cycle Assessment of a Community-Based Wastewater Treatment and Resource Recovery System: Sewage Heat Recovery and MBR for Water Reuse

by

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Abstract

Municipal sewage contains significant embedded resources in the form of chemical and thermal energy. Recent developments in sustainable technology has pushed for the integration of resource recovery from household wastewater to achieve net zero energy consumption and carbon neutral communities. Sewage heat recovery and fit-for-purpose water reuse are options to optimize the resource recovery potential of municipal wastewater. This study presents a comparative life cycle assessment (LCA) focused on global warming potential (GWP), eutrophication potential (EUP), and human health – carcinogenic potential (HHCP) of an integrated sewage heat recovery and water reuse system for a hypothetical community of 30,000 people. Conventional space and water heating components generally demonstrated the highest GWP contribution between the different system components evaluated. Sewage heat recovery-based district heating offered better environmental performance overall. Lower impact contributions were demonstrated by scenarios with membrane bioreactor (MBR)/chlorination prior to water reuse applications compared to scenarios that use more traditional water and wastewater treatment technologies and discharge. The LCA findings show that integrating MBR wastewater treatment and water reuse to a district heating schema could provide additional environmental savings at a community scale.

Preface

This thesis is an original work by Ludwig Paul B. Cabling under the supervision of Dr. Yang Liu and guidance of Drs. Yumi Kobayashi, Nicholas Ashbolt, and Evan Davies. Sections of this thesis have been incorporated into a publication as Cabling, L.P.B., Kobayashi, Y., Davies, E.G.R., Ashbolt, N.J., and Liu, Y. (2020). Life cycle assessment of community-based sewer mining: Integrated heat recovery and fit-for-purpose water reuse. Environments, 7(5), 36.

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1. Introduction

Rapid technological expansion and continued global population growth resulting in increasing demands for clean water calls for innovative water systems (Liu et al., 2017). One direction to tackle these challenges is through the development of emerging sanitation systems integrated with resource recovery. Circular economy thinking and the field of industrial ecology have grown in recent years from environmental considerations being increasingly recognized and prioritized, and as innovations push the limits of how we can address many global concerns (OFID & Development, 2018). Water conservation, efficiency, and sustainable development enable the reduction of greenhouse gas (GHG) emissions, one step towards achieving climate change and clean growth initiatives (del Borghi et al., 2020). Many emerging technologies and sustainable development concepts aim to address water scarcity issues that many countries are currently facing (Ng, 2018; Tortajada & Fernandez, 2018), particularly due to extended hot dry conditions and growing population (Wright, 2019). 71% of the world's irrigated area and 47% of large cities are characterized as experiencing at least periodic water shortage (Brauman et al., 2016). Municipalities and cities of various developed nations have committed to goals for building efficiencies for water reduction and energy use, such as Seattle's district goal to reduce stormwater runoff and potable water use by 50% by 2030 (Seattle 2030 District, 2020), and more locally, Edmonton's *The Way We Green* strategic plan (City of Edmonton, 2011). Edmonton's strategic plan identifies many objectives to respond to various water challenges, notably, to promote high standards of treatment and reduced loadings from the local wastewater treatment utility and to promote water conservation and efficient water use.

As technologies continue to develop, assessments of economic, social, and environmental implications will aid in supporting decision-makers to develop urban water systems more sustainably. Various tools and techniques have been used in water and wastewater sectors to understand how these emerging technologies will function in macroeconomic, social, and environmental contexts. A recent review listed Scenario Analysis, Integrated Assessment Modelling (IAM), Robust Decision Making (RDM), Life Cycle Assessment (LCA), Computable General Equilibrium Model (CGE), and Data-driven Models (DDM) as existing models that have been applied to water-systems-related decision-making processes for a variety of contexts (Namany et al., 2019). Some of the features of these analyses are for holistic decision-making that suggests potential and solutions for energy-food-water nexus systems for a resilient urban development (RDM), to an environmental assessment framework based on the quantification of different synergies existing between energy-food-water nexus systems as a decision-making tool in food security cases (LCA). LCA is a method to quantify impacts associated with all stages of a product, process, or service from cradle-to-grave (ISO, 2006). It has been used in water (Bonton et al., 2012) and wastewater sectors (Corominas et al., 2013) to understand the environmental sustainability of conventional systems, and more recently to comparatively evaluate emerging technologies. However, due to the case-specific basis of LCA, the results provide a snapshot of impacts and should be applied based on explicit contexts.

LCA investigations have been done on a wide variety of technologies, particularly wastewater treatment plants (WWTPs) for conventional activated sludge (AS) systems. For instance, electricity or operational energy consumption has been found by various studies to be one of the main contributors of Greenhouse Gas (GHG) emissions in conventional WWTPs (Corominas et al., 2013). However, as the nature of LCA studies are case specific, this knowledge may only be used in the context based on specific configurations or study regions. The concept of extracting wastewater from an existing sewer to be reclaimed as reusable water (sewer mining) emerged largely from the need to reduce pressure on water resources in Australia (Makropoulos et al., 2018). Community-based wastewater treatment using aerobic membrane bioreactors (MBRs) and chlorine disinfection is now a mature and available technology to produce effluent suitable for water reuse purposes (Krzeminski et al., 2017; Schoen et al., 2017). Further, sewage heat recovery systems are an attractive waste-to-resource approach that has also been gaining interest in recent years (Culha et al., 2015; Liu et al., 2014). Sewage heat can be captured and optimized for a district heating system wherein reductions in CO_2 emissions can be demonstrated from the conversion of fossil fuel sourced electricity heated homes to community heating using alternative energy sources (City of Vancouver, 2020; Joelsson & Gustavsson, 2009), particularly since domestic space heating and hot water provision represent the largest share of energy consumption associated with residential building operations (Torío & Schmidt, 2010).

Previous studies have explored the integration of water, waste, and energy management systems in various cases, i.e. Curauma, Chile (Vergara-araya et al., 2020), as well as energy and nutrient recovery in municipal wastewater (Foley et al., 2010; Mo & Zhang, 2013; Remy &

Jekel, 2012; Thibodeau et al., 2014). Environmental burdens associated with products and processes based on material and energy uses and releases to the environment have been investigated for building heating (Chau et al., 2015). Recent research has generally found positive environmental performances from the recovery of energy from municipal sewage, with limitations attributed to supply distances and varying regulations/policies (Hao, Li, et al., 2019). Water reuse benefits considered included reduced needs for drinking water production (Kobayashi et al., 2020). In principle, municipal sewage could provide space and water heating for buildings, since operational energy requirements account for about 80-90% of the life cycle energy needs of a building (Ramesh et al., 2010). While the environmental evaluation of different fuels for district heating has been investigated, very few studies have looked at the evaluation of sewage heat recovery, as only few full-scale systems exist to date (Eriksson et al., 2007; Ghafghazi et al., 2011; Pericault et al., 2018). Further, it is probable that operational energy requirements to maintain comfortable conditions and of day-to-day maintenance of a building are higher for cold regions that require longer periods of space heating. However, few studies exist that have evaluated the environmental performance of integrated systems (Corominas et al., 2013) and no known research has been done to date evaluating the cumulative environmental impact of combining a sewage heat recovery system with community-based wastewater treatment for various water reuse purposes.

This study aims to the understand how to further minimize the environmental impacts of residential communities by incorporating a decentralized sanitation and resource recovery scheme consisting of sewage heat recovery and community-based wastewater treatment for water reuse. The sewage heat recovery system considered for this study is based on a full-scale system in South East False Creek, Vancouver, BC, Canada. This system began operations in 2010 and has expanded to serve 534 000 m^2 (5 750 000 ft^2) of residential space as of 2019 (City of Vancouver, 2020). The facility utilizes a two-stage heat pump that recovers waste heat from untreated urban wastewater, demonstrating greater heat potential and lower installation costs compared to most geothermal systems. Insulated underground pipes circulates hot water around the neighbhourhood using energy transfer stations at each building to provide space heating and domestic hot water using radiant floor/ceiling systems, baseboard heaters, and forced-air systems. High efficiency natural gas boilers supply supplemental heat for colder days to maintain domestic heat requirements while supplying energy at a competitive cost (City of Vancouver, 2020). This study investigates the environmental performance of applying integrated resource recovery technologies from wastewater serving a hypothetical community development of 30,000 people, using previously identified key parameters (Xue et al., 2015) to determine possible benefits of decentralized water and wastewater infrastructure compared to business as usual. Using a life cycle assessment methodology, a waste-to-resource schema was hypothesized to have lower environmental impact values of global warming potential (GWP), eutrophication potential (EUP), and human health carcinogenic potential (HHCP) compared to a system that uses conventional technologies for both wastewater treatment and the provision of hot water and space heating.

2. Literature Review

2.1. Municipal Wastewater Systems

Conventional municipal WWTPs that function in many well-developed urban regions usually consists of multiple stages (primary, secondary, and advanced stages) with the use of various biological and chemical treatments. Large scale centralized municipal WWTPs often rely on conventional gravity sewer systems, which are the most common technology used to collect and transport domestic water despite high construction and maintenance costs (US EPA, 2002). Alternative options to the conventional centralized technologies are oxidation ponds and septic tanks. Oxidation ponds are an older wastewater management technique that uses natural processes to effectively decompose organic matter, while septic tanks are constructed to separate solids from incoming wastewater, using anaerobic biological digestion to digest organic waste, producing a residual sludge (septage) to be disposed of, and wastewater that is channeled into a drain field (Gerba & Pepper, 2019). Different wastewater treatment options are necessary to fulfil a variety of considerations regarding scale, influent quality, desired effluent quality, budget, and more recently, environmental sustainability. Research has shown that aeration accounts for 60% of the energy distribution of conventional activated sludge systems, followed by wastewater pumping (12%), grit removal (11%), and lighting and building requirements (6%) (Gu et al., 2017). Environmental impacts that are associated with conventional wastewater treatment processes include climate change and anthropogenic GHG emissions of mainly CO_2, CH_4, and N_2O, which come from various sources at the WWTP level (Kosse, 2018).

Alternatively, conventional centralized WWTPs may be outfitted with resource recovery technologies with the goal of reducing environmental burdens by offsetting the high operational requirements of conventional processes (Hao, Wang, et al., 2019). Innovations in modular wastewater treatment technologies create opportunities to redesign conventional systems and operations (Zodrow et al., 2017). Failing wastewater infrastructure (Anbari et al., 2017) due to leaks, high costs of maintenance, and public health concerns due to old pipes of current potable water infrastructures (Arsénio et al., 2015) are challenges that may be addressed by alternative urban water and wastewater designs. Decentralization is an option to potentially decrease the costly damage and health risk that a massive, centralized infrastructure failure may impose.

2.2. Sewer Mining

Sewer mining is the concept of the extraction, treatment, and re-use of wastewater from a sewer main. Emerging from water crises in Australia, innovations in water reclamation have enabled waste-to-resource thinking for regions, many with ambitions of sustainable development for their communities. Embedded chemical and thermal energy from municipal sewage can now be seen as a valuable resource that can be extracted, not only to further save on energy costs, but also to reduce the environmental implications of conventional water and energy systems. Positive economic implications are also associated with sewer mining, particularly in presenting an opportunity for Small Medium Enterprises (SME) to be involved in the water market (Makropoulos et al., 2018). Beyond on-site treatment for water reuse, the concept of sewer mining can be further understood as the extraction of wastewater for the purposes of energy and nutrient recovery. Heat pumps have been utilized for many manufacturing industries and have matured as a technology in the past four decades (Chua et al., 2010). Alongside industrial uses of heat pumps, early research has demonstrated the performance of sewage as a source of energy which can be used for heating and cooling buildings using heat pumps (Schmid, 2008). Municipal wastewater temperatures tend to be between 10-30˚C, varying slightly by region and climatic factors (Hao, Li, et al., 2019; Schmid, 2008), and have reliable and available flow rates throughout the year, making sewage a suitable option for a water source heat pump for the recovery of low-grade heat/cold. Government institutions may also be a part of enabling such sustainable systems, such as the South East False Creek Neighbourhood Energy Utility (SEFC NEU) in the City of Vancouver, which uses sewage waste heat as a source for their neighbourhood renewable energy system to meet goals of cutting carbon emissions and reducing fossil fuel dependence (City of Vancouver, 2020).

Odour and corrosion in sewer systems due to sewer mining is one issue that should be addressed. While sewer mining may reduce hydrogen sulphide concentration at the sewage extraction points, downstream disposal and accumulation results in higher hydrogen sulphide concentrations leading to higher odour occurrence and corrosion rates (Marleni et al., 2013). There are many sources of environmental releases that should be investigated to compare with potential sewer mining releases, for instance construction and operational stages of urban wastewater systems (i.e. sewer infrastructure systems and wastewater treatment plants). An LCA conducted by Risch et al. (2015) found that the construction stage of sewer infrastructure has greater environmental impact than both the construction and operation of the studied WWTP, which highlights the importance of including construction and operational phases when making an environmental assessment between centralized and decentralized urban water systems.

The concept of sewer mining may be a key transitional step towards decentralization of wastewater treatment systems, considering that current urban water and wastewater infrastructures exist and will continue to require maintenance for years to come. Meanwhile, as future greenfield developments implement decentralized options or as hybrid developments are built, waste-to-resource integrations can be built in conventional urban infrastructure. As such, sewer mining can emerge as one of many different resource recovery initiatives, particularly one that may play a significant role in addressing regional water scarcity and energy needs.

Different types of treatment technologies have been used for sewer mining applications. Xie (2014) used a forward osmosis (FO) - membrane distillation (MD) hybrid system for small-scale decentralized sewer mining. The lab-scale FO-MD hybrid system operated continuously with raw sewage as the feed at water recovery up to 80%. Excellent removal of trace organic contaminants (TrOCs) was observed (removal rates 91-98%) and is shown that the TrOC transport through the FO membrane is governed by solute-membrane interaction, whereas through the MD membrane is strongly correlated to TrOC volatility. Previous studies have indicated evidence of TrOC impacts to the aquatic environment alongside human health impacts related to physiological processes, reproductive impairment, incidences of cancer, and development of antibiotic-resistant bacteria (Xie, 2014).

Research in evaluating the environmental impacts from potable water production has shown that the production stage contributes the highest impact on acidification and eutrophication, which has been derived from requirement of aluminum chloride (alum), polyaluminum chloride (PAC), and chlorine and calcium hydroxide (lime) (Sharaai et al., 2011). This study also indicated that the construction stage contributes two main impacts of human toxicity (water) and chronic water ecotoxicity.

2.2.1. Sewage Heat Recovery Options

While waste-to-resource concepts in wastewater systems are mostly associated with chemical energy recovery, recent research indicates significantly higher thermal energy recovery potential than chemical energy potential (Hao, Li, et al., 2019). The heat of untreated wastewater is usually unrecognized as a source of energy due to perceptions of sewage as waste instead of a resource. In the Netherlands, a study showed that annual energy demand for tap water in houses is almost eight times more than both drinking water collection and treatment processes combined (Frijns et al., 2013). This study also noted that for Dutch households, 60% of their drinking water is heated to a set temperature. These conditions can be similarly assumed for regions of similar climate or water needs, such as parts of North America. A review has been done on the various options exist to recover the embedded heat in water using heat exchangers (Culha et al., 2015). The various types of wastewater heat exchangers used in studies and commercial applications are as listed: 1) Gravity film heat exchanger (HEX), mostly applied to domestic drainage systems but has lower heat recovery capacity; 2) Helical HEX, which can be applied to both domestic and after WWTP applications; 3) Plate HEX, used in domestic heat recovery and after WWTP applications; 4) Pressure pipe HEX, applied around channels which have high pressure flow inside the pipe to avoid pressure loss in the channel. Performance varies between 0.6 and 6.3 kW/m depending on pipe dimension; 5) External systems, clean water flows inside tubes and pre-filtrated WW flows in a tank. These are mostly applied to sewage systems with extra pumping and piping systems; 6) Integrated systems, mostly applied to new-build sewage lines. HEX pipes are integrated into the channel during channel excavation; 7) Modular systems, where designs are based on channel size and flow quality of sewage and can be applied to existing sewage channels by bypassing the existing flow inside the channel.

2.2.2. Wastewater Treatment Options

Various treatment options for modern sewer mining applications have been reviewed in Australia, such as dual membrane, moving bed biofilm reactors, reverse osmosis (RO), reed beds, membrane bioreactors (MBRs), and sequencing batch reactors (SBRs), and ultraviolet (UV) disinfection (Makropoulos et al., 2018). These various options provide non-potable water for irrigation of public and domestic green spaces.

A membrane bioreactor (MBR) is a technology that provides both biological treatment with membrane separation and is typically a packaged activated sludge system with an ultra-filtration membrane replacing the secondary clarifier (**Figure 1**). The MBR was introduced as an alternative to conventional activated sludge processes by using membranes. A higher mixed liquor suspended solids (MLSS) concentration or simply the concentration of suspended solids in an aeration tank can be operated with an MBR, resulting in a smaller footprint (Karna & Visvanathan, 2019). The main challenge of MBRs is the requirements to either have higher suspension flow rate recycles throughout the membrane to minimize the fouling rate, which results in increased energy consumption, or the requirement for extensive cleaning protocols when drastic membrane fouling occurs (Karna & Visvanathan, 2019). This filtration process enables the removal of bacteria, microorganisms, and other insoluble solids, resulting in a high-quality effluent that may be used for various water reuse purposes. The recent trend for MBR operational conditions is to use a lower SRT (10-20 days) and lower MLSS concentrations (10-15 mg/L), with a performance of almost 100% removal of suspended solids and more than 90% of chemical oxygen demand (COD) resulting in high-quality effluent (Karna & Visvanathan, 2019).

LCAs have been conducted for MBR applications, particularly to treat municipal wastewater. A compilation of these studies is shown in **Table 1** from Web of Science database searches and the most recent review articles by Hospido et al. (2012) which investigated the environmental performance of MBRs by evaluating different configurations and discussed the possible correlation between operational conditions and environmental profiles; and Krzeminski et al. (2017), which discussed recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects, and interpreted a comparison between standard MBR, AnMBR, BF-MBR, MABR, and FO-MBR against energy demand and impacts on climate change, fresh water, and marine eutrophication. **Table 1** is characterized based on the year, scale of study, environmental impacts considered, and functional units (FU) used. As most of these studies have a focus on treatment processes of MBRs, the FU typically used has been based on a per volume of water treated. This is a standard that may enable multiple studies to be compared to each other, either with the use of the same or different treatment technologies. However, as is shown on **Table 1**, study scales largely vary, which mostly impedes the potential to compare studies with one another. Significant differences are observed for the environmental impact methodologies used for the various studies. This however is more indicative of the study's region, for instance, the two studies based in the US used TRACI indicators, while most of the European studies considered Eco-Indicator or CML baseline indicators. Most studies however included a CO_2-related impact indicator as impacts associated with energy consumption is most commonly represented by carbon emissions.

Comparisons between varying scales based on similar treatment processes however may prove to be useful, especially when LCA results are used for specific decision-making processes. Kobayashi et al. (2020) for instance evaluates three different scales of community-based water reuse, such as at a household scale (up to 5 population equivalent or PE), neighbourhood scale (350 PE), and community scale (3500 PE), recognizing the applicability of these technologies, and highlighting the environmental performances of the various components of the system processes. The different methodologies and programs used for the various LCA studies should always be clearly communicated when making comparative judgements between studies, which is markedly strenuous due to the variances of units and impact indicators of different methodologies. Energy consumption has typically been the basis of environmental evaluations for many MBR studies because operational energy consumption relates closely to economic costs.

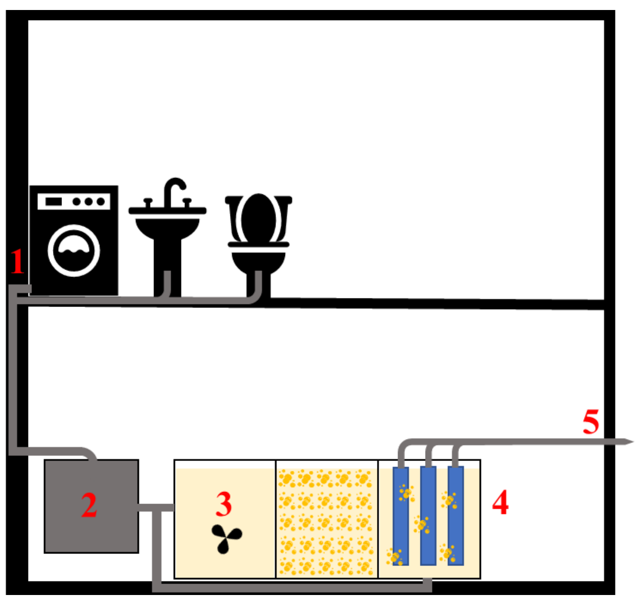

Figure 1. Membrane bioreactor. System components: (1) Collection system, (2) Pretreatment, (3) Aeration, (4) Membrane, (5) Distribution system for either outdoor or indoor reuse.

Table 1. Life cycle assessments of MBR applications.

Author & Year	Location	Scale	Environmental Impacts [a] or Method Considered	Functional Unit
Tangsubkul et al., 2005	Sydney, Australia	5 ml wastewater treated per day, medium strength wastewater, 80 kg/ml dry sludge production	GWP, EP, HTP, FAETP, MAETP, TETP, SP	1 ml of recycled water to be used for irrigation of sensitive crops.
Ortiz et al., 2007	Spain	External and immersed MBR based on 3,000 m^3/day	Eco-Indicator 99, Eco-Points 97, CML baseline 2000	Production on average of 3,000 m^3/day of water for 25 years (membrane replacement every 7 years).
Memon et al., 2007	UK	Used 20 development scales to develop a tool using the adaptive neuro-fuzzy inference system technique.	CML 2 baseline (v2.1), Eco-Indicator 99	Volume of treated greywater to be produced by the treatment system over its designed life span.
Høibye et al., 2008	Denmark / EU	Treatment of 50,000 m^3 municipal wastewater per day; lifetime treatment technology of 20 years.	GW (greenhouse gases in CO_2-equivalents), AC, NR, ET, heavy metals, endocrine disruptors	Global warming calculated per 1 m^3 of treated water; Ecotoxicity calculated per m^3.

Cascadia Green Building Council, 2011	WA, US	For a population of 83,000 customers for a neighbourhood scale (2,500 MBR units serving approximately 33 customers each.	TRACI indicators: GW, OD, AS; IO_2+v2.1 midpoint indicators: ATA (kg SO_2-Eq), AE (kg TEG-Eq), AEU (kg PO_4-Eq); RE (kg $PM_{2.5}$-Eq)	The ability to treat the annual wastewater generated by a population of 83,000 customers over a 50-year time span.
Ioannou-Ttofa et al., 2016	Cyprus	Designed treatment of 10 m^3/day of primary wastewater with a useful lifetime of 20 years.	ReCiPe midpoint indicators: CC, OD, TA, FEU, MEU, HT, POF, PMF, TET, FET, IR, FET, MET, IR, ALO, ULO, NLT, WD, MD, FD	Effective treatment of 1 m^3 urban wastewater
Holloway et al., 2016	Nordkanal, Germany	48,000 m^3/day (12.7 MGD)	Waste-Water-Energy Sustainability Tool (WWEST)	Production of 1 m^3 of reusable (potable and/or non-potable) water
Chen et al., 2018	Kunming, China	Large scale anaerobic/anoxic/oxic (AAO)-MBR plant with a capacity of 60,000 m^3/d	CML 2001 midpoint categories: AQA, AE, AEU, CAR, GWP, IR, LO, LO, ME, NCAR, NRE, OLD, PO, RE, TA, TNI, TET	1 m^3 of treated water
Cashman et al., 2018	Bath, NY, US	1 MGD (3800 m^3/d), approx. 5600 people.	TRACI v2.1: GHG using IPCC 2007 Fourth Assessment Report (AR4) GWPs; Energy based on point of extraction and higher	1 m^3 of treated wastewater

			heating value using the CED method	
Dominguez et al., 2018	Santander, Cantabria, Spain	Based on hotel laundry to treat greywater with 50 mg/L of sodium dodecylbenzenesulfonate (SDBS); Hotel of 75 guests	Institution of Chemical Engineers environmental burdens impact categories atmospheric burdens: ATA, GW, HHE, POZF, SOD; water burdens: AQA, AE, AQOD, MEco, NMEco, EP	1 m^3 of treated greywater with 90% reduction of (SDBS)
Ashok et al., 2018	Bangalore, India	500 m^3/day operated for 24 hours a day (in three shifts of eight hours each)	Limited to energy consumption, flow characteristics, and water quality.	1 m^3 of treated wastewater
Kamble et al., 2019	India	0.8 MLD capacity plant	CML 2001: ADP, ELE, FD (MJ), AC (kg phosphate-Eq), EP, FAETP (kg DCB-Eq), GWP (kg CO_2-Eq), HTP (kg DCB-Eq), MAETP (kg DCB-Eq), ODP (kg R11-Eq), POCP (kg Ethene-Eq), TETP (kg DCB-Eq)	1 m^3 of treated wastewater
Akhoundi & Nazif, 2020	Tehran Province, Iran	Based on 450,000 m^3/day municipal wastewater produced	Impact 2002+: HTP, AE, TE; Eco-Indicator 99, CML 2001, Intergovernmental Panel on	Production of an average of 1 m^3/day of WWTP effluent during 20 years

			Climate Change (IPCC), and cumulative energy demand.	(the estimated useful lifespan of the WWTP).
Ribera-Pi et al., 2020	Orís, Spain	A side stream 23 m^3 MBR pilot plant being used as a pre-treatment of 1,300 m^3 of landfill leachate along 146 days of operation.	ReCiPe 2016 Midpoint (H) method	Treatment of 1 m^3 of leachate that met the quality standards to be discharged into water bodies or sent to a WWTP
Kobayashi et al., 2020	Edmonton, Canada	MBR for water reuse at 3 different scales	TRACI: OD, EP, GWP, AC, RE, HHCP, FD, POF	Annual treatment of greywater generated per person.

[a] AC: Acidification; ADP: Abiotic Depletion Potential; AE: Aquatic Ecotoxicity; AEU: Aquatic Eutrophication; ALO: Agricultural Land Occupation; AQA: Aquatic Acidification; AQOD: Aquatic Oxygen Demand; AS: Air Smog; ATA: Atmospheric Acidification; CAR: Carcinogens; CC: Climate Change; ELE: Elements; EP: Eutrophication Potential; ET: Ecotoxicity; FAETP: Freshwater Aquatic Ecotoxicity Potential; FD: Fossil Depletion; FET: Freshwater Ecotoxcity; FEU: Freshwater Eutrophication; GW: Global Warming; GWP: Global Warming Potential; HHE: Human Health Effects; HT: Human Toxicity; HTP: Human Toxicity Potential; IR: Ionising Radiation; LO: Land Occupation; MAETP: Marine Aquatic Ecotoxicity Potential; MD: Metal Depletion; ME: Mineral Extraction; MEco: Ecotoxicty - metals to seawater; MET: Marine Ecotoxicity; MEU: Marine Eutrophication; NCAR: Non-Carcinogens; NLT: Natural Land Transformation; NMEco: Ecotoxicty - other substances; NR: Nutrient Enrichment; NRE: Non-renewable Energy; OD: Ozone Depletion; OLD: Ozone Layer Depletion; PMF: Particulate Matter Formation; POCP: Photochemical Ozone Creation Potential: POF: Photochemical Oxidation Formation; POZF: Photochemical Ozone Formation; RE: Respiratory Effects; SOD: Stratospheric Ozone Depletion; SP: Salinisation Potential; TA: Terrestrial Acidification; TET: Terrestrial Ecotoxicity; TETP: Terrestrial Ecotoxicity Potential; TNI: Terrestrial Nitrification; ULO: Urban Land Occupation; WD: Water Depletio

2.3. Use of Life Cycle Assessment in Wastewater Treatment

Life cycle assessment (LCA) is a tool that can be used to comparatively assess the environmental performance of a product or system, whereby various environmental interactions of associated system phases, i.e. raw material extraction, construction, operation, and disposal or recycling, are quantified. The International Organization for Standardization (ISO) 14040 and 14044 standards (ISO, 1997, 2006) is a widely recognized basis for the principles and framework for LCA. The standards however do not provide detailed methodologies for the assessments, of which is typically unique to the software used and the goals and objectives of the study.

Generalized reviews have been done on LCA in wastewater treatment technologies (Corominas et al., 2013; Parra-Saldivar et al., 2020) which identify the current types of LCA framework use for sanitation systems, as well as the key environmental impact contributors associated with such processes. This study plays a role in the paradigm shift from pollutant removal to resource recovery, whereby alternative options to conventional systems are investigated through the environmental lens of sustainability.

Research has also been done on understanding point source emissions and infrastructure impacts of various urban stormwater systems, particularly integrated with risks associated with stormwater discharges (Brudler et al., 2019). Stormwater discharges has been found to contribute significantly to the total ecosystem damage of different generic stormwater management systems (36-88%) (Brudler et al., 2019). The researchers found that combined sewer systems cause significant infrastructure-related impacts and low point source emission impacts, with green infrastructure having significantly lower infrastructure impacts due to limited material and operational demands. Future studies may apply point source emission impacts for water reuse technologies, signifying the impacts resulting from reclaimed water discharged. Inclusions of emissions to soil, like N or P discharge on land due to the use of reclaimed water for irrigation have be considered with LCA (Lackey et al., 2020). Evidently, considerations of more components to be included as part of the impact contributions of a system is ideal, however, such comprehensive LCA studies are considerably difficult to achieve. As such, LCAs aim to have specific goals with pre-defined targets to be investigated, such as energy consumption or environmental pollutant releases.

Life cycle costing (LCC) or an economic assessment based on the life cycle of a product or a process is the other component of the triple bottom line or three pillars of sustainability. This tool evidently may play an important role in water management and decision-making processes, alongside social life cycle assessment (S-LCA), which is often assessed based social components which are typically qualitative information rather than quantitative (Jørgensen et al., 2008). Benefits of alternative approaches to urban domestic non-potable water reuse have been determined with S-LCA by previous research (Opher, Shapira, et al., 2018). Various water and wastewater treatment options have been assessed by cost analyses in membrane bioreactor (MBR) systems (Cashman & Mosley, 2016), small scale anaerobic digestion (AD) with co-digestion of high strength organic waste (Morelli et al., 2018), and systems for urban water reuse (Opher, Friedler, et al., 2018).

2.4. Gaps in Literature

To date, there is no research on assessing a combined heat recovery and wastewater treatment schema. Independent systems of various heat recovery and wastewater treatment configurations have been assessed in recent years as advanced resource recovery applications from municipal wastewater are still in the development stage (Mo & Zhang, 2013; Morelli et al., 2018). This thesis fills this gap in literature of assessing integrating these systems together, as various environmental performances are at play which have not been recognized when these systems are analyzed individually. Further, while a sewage heat recovery schema is aimed to be developed in the case study location for this assessment (City of Edmonton, 2019), this study presents a life cycle assessment and methodology which has not yet been done. The applicability of this study is part of the research body pertaining to the sustainability framework of emerging water services focused on resource recovery. The research methodology of this study can be replicated for future evaluations of environmental performances for modified versions of the study scenarios or for new configurations of similar systems and new technologies. The data and literature used to develop and support this study are outlined in this thesis, and can be altered for the purpose of future assessments to understand changes in environmental performances when new data are collected on construction and operational components for future configurations and applications.

2.5. Technologies and Systems for Future Evaluations

This section discusses the different systems being evaluated in the study, as well as other potential options that should be considered in the future. A myriad of sustainable alternatives to traditional water and wastewater services. Decentralized concepts for instance are now known as a sustainable alternative where conventional sanitation has not yet been established. Here, decentralized options are synonymous to *community-based systems*. Further, a variety of options can be used in a decentralized schema, particularly when wastewater treatment for water reuse is considered. MBR technology is used here for this purpose; however, new options that have not yet been adaptived in many full-scale applications offer additional environmental savings, such as the membrane aerated biofilm reactor (MABR) discussed below. Upflow anaerobic sludge blanket (UASB) technology is another option that is well established for treating a variety of wastewaters, but has recently been a focus for treating municipal blackwater (waste from toilets or urinals) due to low energy and operational costs, lower production of waste sludge, and the generation of energy in the form of methane (Xu et al., 2018). System dynamics is a tool that can be used to simulate multi-variable interconnections, feedbacks, and coevolution, particularly in the context of water systems (Forrester, 1987; X. Zhang et al., 2019). In developing future technologies, system dynamics plays a role in understanding the feasibility and adoption of these new applications. It is important to recognize these other tools that enable a holistic decision-making process.

2.6. Decentralized Wastewater Treatment Technologies

Decentralized systems for the treatment of domestic effluents have been shown to be a sustainable option for greenfield developments that have no existing centralized systems and for communities that require significant changes to their conventional urban water systems due to aging infrastructures (Zodrow et al., 2017). Decentralization in water and wastewater infrastructure is commonly understood as the alternative to conventional technologies that are built based on the concept of an extensive conveyance system. Currently there are challenges for decentralized applications in a large-scale, considering the dominance of conventional technologies and systems as well as the various utility stakeholders involved. Decentralization can be a concept that could be understood as a transitional phase or technology, wherein a hybrid approach of conventional infrastructure and innovative technologies can function as rapid expansion and development of new technologies arise.

Implementation and regulation of onsite non-potable water systems are required to take advantage of a waste-to-resource concept. Presently, many regions in Canada do not have the regulatory framework for water reuse technologies, likely due to the lack of demand from available water resources, despite many municipalities regularly experiencing water supply shortages (Schaefer et al., 2004). References have been compiled by Lackey et al. (2020) for the development and implementation of onsite non-potable water systems, which is a vital part towards the promotion and development of such systems in Canada.

2.6.1. Upflow Anaerobic Sludge Blanket (UASB) Reactor and Blackwater Treatment

While anaerobic wastewater treatment is a well-established technology and has been readily applied at the full scale, some technologies, like the upflow anaerobic sludge blanket (UASB) reactor, which only have few studies that have been applied at the full scale for domestic wastewater treatment. The benefit of UASB technology is determined by its produced biogas with a high calorific value, which typically has been neglected and flared to the atmosphere (Rosa et al., 2018). UASB technology also plays a role in source-separated wastewater streams, whereby separated blackwater from domestic wastewater and other waste sources like food-waste can be utilized to maximize bioenergy recovery through anaerobic co-digestion (Gao et al., 2020).

Few studies have been done on the environmental assessment of UASB applications. Recently Prado et al. (2020) conducted an LCA on various scenarios for on-site reuse of blackwater and kitchen, of which utilized a UASB reactor. This research concluded the reduction of energy consumption as the most relevant factor for minimizing environmental impacts, noting that the level of blackwater treatment did not result in significant changes. The evaluation of integrating wastewater treatment systems (UASB with an anaerobic filter and photoreactors) with natural alternatives such as constructed wetlands has been investigated and found that while the anaerobic unit accounts for most of the environmental impacts mainly related to climate change, energy recovery from the anaerobic unit will reduce environmental pressure indexes (Lutterbeck et al., 2017). The study also recognized the environmental benefits that resulted from water reuse, despite impacts from construction and operation of the phototreatment unit. Studies investigating UASB applications should focus on the reduction of energy consumption due to pumping and mixing which in the case of the study done here can be recognized in the operational energy requirements of MBR systems, pumping requirements for water collection and distribution, and energy inputs from the heat pumps.

Integrating more complex resource recovery systems such as UASB reactors into the heat recovery and water reuse schema studied here would evidently require significant study to capture the extent of environmental savings from integrating such resource recovery technologies.

2.6.2. Membrane Aerated Biofilm Reactor (MABR)

Different from membrane biological reactors, MABRs diffuses oxygen supplied from the lumen of a membrane filter to the outer surface that enables the formation of a biofilm layer that supports the growth of nitrifying and denitrifying bacteria as well as heterotrophs that utilize carbon for their growth and development. The MABR benefits from the reduced footprint of the system without requiring a secondary clarifier, alongside the characteristics of simultaneous nitrification and denitrification processes with reduced energy consumption linked to aeration processes, reported as 0.1-0.2 kWh/m^3 versus conventional activated sludge systems (CAS) at 0.27-1.89 kWh/m3 (Karna & Visvanathan, 2019).

Existing research on assessing conventional municipal wastewater systems has shown components where systems can be optimized for environmental performance. Decentralized urban water infrastructure is one approach at increasing sustainability metrics by maintaining local management of water and wastewater services. As technology development is currently a focus, limited research has been done on assessing conventional and emerging technologies, a component which plays a role in the acceptance and application of alternative options. Current studies on MBR wastewater treatment and sewage heat recovery have been reviewed to understand the role of assessing these technologies for the successful adoption of environmentally sustainable alternatives.

3. Materials and Methods

This section explains the LCA methodology used and the LCI inventory required for this study.

3.1. Life Cycle Assessment Methodology and Framework

The life cycle assessment methodology is composed of multiple stages: goal and scope definition, the life cycle inventory (LCI) analysis phase, life cycle impact assessment (LCIA), and the interpretations of the results. The overall research framework and approach is shown in **Figure 2**. Here, we begin the first stage of the study, which is composed of the purpose, scope, and main hypotheses, and selects a functional unit (FU) to signify a reference value representing the flows and emissions of the study systems.

The goal of this study was to evaluate the environmental performance of a community-based sewage heat recovery and water reuse schema for the purpose of informing decision-makers on the environmental implications of such systems. The results of the study are intended to be used to compare between conventional and unconventional technologies.

Current research shows a multitude of environmental benefits from sewage heat recovery (Culha et al., 2015; Liu et al., 2014) and water recycling (Schoen et al., 2017). Thus by combining sewage heat recovery technology with wastewater treatment for water reuse, environmental impact reductions can be further achieved. Generally, it is understood that the reduction of the serviceable distance of such decentralized technologies reduces the environmental impacts that are otherwise in place if centralized systems are used, understanding that water conveyance operation and infrastructure should be recognized as a key contributor in carbon and energy footprints (Griffiths-Sattenspiel & Wilson, 2009; Y. Liu et al., 2016).

The FU chosen was the annual provision of the following services per person: home space heating, hot water, and various types of water uses such as irrigation (IR), toilet flushing (TF), and clothes washing (CW). The chosen FU is based on the unique case of integrating wastewater heat recovery and water reuse applications. Commonly, an FU of per volume of treated wastewater has been used for LCAs as a general standard to compare different treatment configurations across different studies. However, with the case-specific nature of life cycle studies, comparisons between different studies that have different goals are difficult.

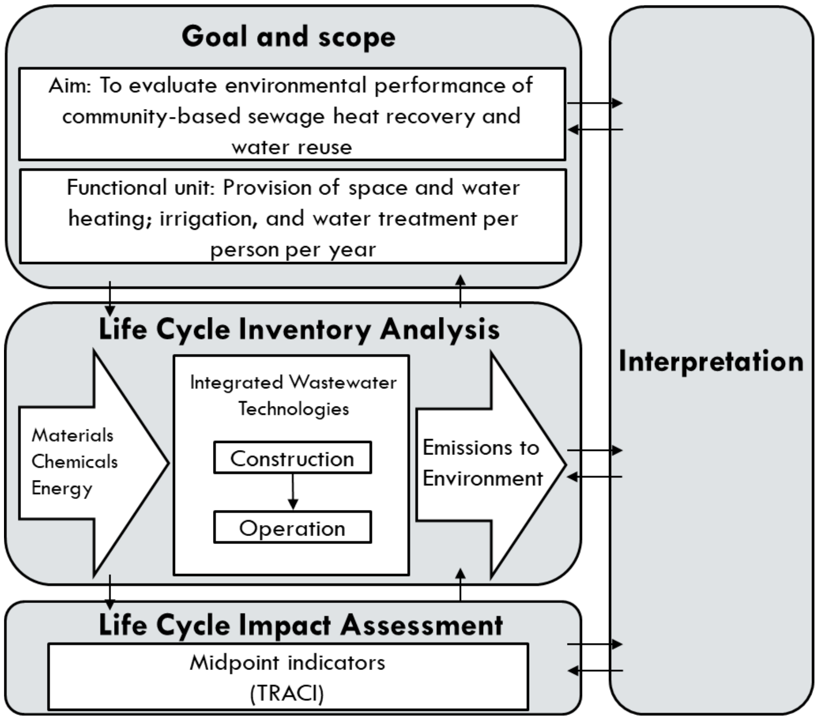

Figure 2. Overall research framework and approach.

3.2. Community System and Problem Framing

The greenfield community modelled for the study was based on a hypothetical community consisting of individual homes for a 30,000 person-equivalent (PE) population in the City of Edmonton (32.54° N, 113.49° W), Alberta, Canada. This region was chosen as a planned community (Blatchford) is underway to demonstrate a district heating system that utilizes renewable energy sources such as sewage heat recovery and shallow geothermal systems (City of Edmonton, 2019). The environmental performance integrated an ambient district heating system with community-based wastewater treatment for water reuse was determined by three scenarios: (1) Business-As-Usual (BAU), (2) District Energy System (DES) using Sewage Heat Recovery (SHR), and (3) DES with Membrane Bioreactor (MBR) treatment as shown in **Table 2**.

Table 2. LCA study scenario types

Scenario category	Heating system	Water treatment system	Wastewater treatment system	Wastewater Reuse	Water Use Application
BAU	Conventional gas furnace and water heater	Conventional water treatment plant	Conventional wastewater treatment plant	x	IR
					IR+TF
					IR+TF+CW
DES	Sewage heat recovery for district heating	Conventional water treatment plant	Conventional wastewater treatment plant	x	IR
					IR+TF
					IR+TF+CW
DES+MBR	Sewage heat recovery for district heating	Membrane bioreactors		✓	IR
					IR+TF
					IR+TF+CW

BAU: Business-as-usual; DES: District energy system; MBR: Membrane biological reactor; IR: Irrigation; TF: Toilet flushing; CF: Clothes washing

3.2.1. Business-As-Usual

The baseline scenario used in this study consisted of conventional single-family semi-detached homes with 2 units per building for 30,000 people. Considerations for services include water and space heating using an electric furnace, natural gas fired water boilers, tap water provision from a conventional water treatment plant (coagulation, flocculation, and filtration) with disinfection (free chlorine, ultraviolet disinfection, and monochloramine for disinfection) (EPCOR, 2020a), and conventional sanitation services using a centralized municipal wastewater treatment plant including primary treatment, biological secondary treatment, and ultraviolet (UV) disinfection (Cascadia Green Building Council, 2011; EPCOR, 2020b). Conventional space and water heating systems were considered for the BAU scenarios using literature data from an LCA study of residential homes from Michigan, US., which has a comparable seasonal climate to the City of Edmonton (Blanchard & Reppe, 1998). The conventional municipal wastewater system was based on the operational conditions of a local wastewater treatment plant (WWTP) (EPCOR, 2020b), which is the expected wastewater treatment provider for communities within the City of Edmonton. Major inventory components for the WWTP and drinking water production were sourced from literature and the ecoinvent database (EPCOR, 2020b; Wernet et al., 2016). Primary data used from annual waterworks reports focused on chemical consumption of total alum and polymer, and electrical energy consumption of the plant's operation based on the annual average of water volume production from 2010-2018.

3.2.2. District Energy System

The scenarios that include a district energy system use a design based on the average Canadian apartment area of 88 m^2. Using the Canadian average of 3 occupants per dwelling, 10,000 units for 30,000 people were assumed (Natural Resources Canada, 2016). A total floor area of 880,000 m^2 was used for the hypothetical community of the study using DES. A distribution line is implemented for scenarios that include water reuse, representing additional environmental contributions. Characteristics and a general outline of the distribution system is shown in **Table 3** and **Figure 3**, respectively.

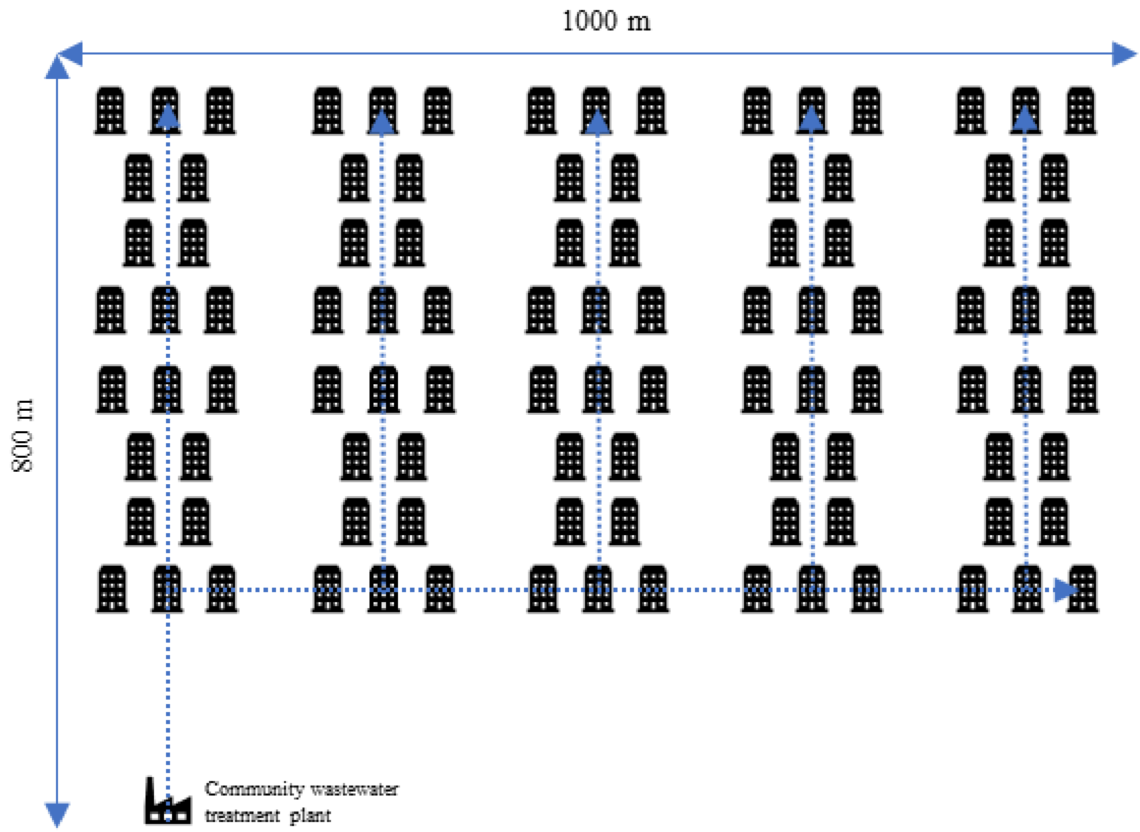

Figure 3. Simplified scale of recycled water distribution system.

3.2.3. Water Use and Reuse

In evaluating the benefits of water recycling, various scenarios were used to simulate different types of water reuse with the use for both conventional tap water production and recycled effluent from membrane bioreactor technology. The basis of water use and reuse for this study is based on household water consumption averages in the City of Edmonton as shown in **Table 3**. The major household water consumption types of irrigation, toilet flush, and clothes washing was chosen, as well as a combination of the three (**Table 4**).

Table 3. Edmonton household water consumption characteristics.

Type of consumption	Fraction of household water consumption (%) [a]	Volume per person per year ($m^3.PE^{-1}.y^{-1}$) [b]
Showers / baths	34	23.1
Outdoor	5	3.4
Kitchen / cleaning	13	8.8
Clothes washing	19	12.9
Toilets	29	19.7

[a] Fraction of household water consumption for the City of Edmonton (City of Edmonton, 2017b).
[b] Daily household water consumption for Edmonton is 186 L/person/day (EPCOR, 2018).

Table 4. Water use / reuse scenarios

Water use / reuse	Total volume of water per year ($m^3.y^{-1}$)
Irrigation	101,835
Toilet flush	590,643
Clothes washing	386,973
Irrigation + toilet flush	692,478
Irrigation + toilet flush + clothes washing	1,079,451

The community-based MBR configuration used for this study included screening as a pre-treatment, ultra-filtration for the main treatment, and chlorination for disinfection. A simplified recycled water distribution system was assumed with its additional materials and operational process requirements.

3.2.4. System Assumptions

- Material transport was generalized using the ecoinvent global market databases (v3.5) to account for average transport impacts.
- 10,000 detached housing units representing 30,000 EP based on standard community developments for the City of Edmonton.
- Heating distribution building components, such as radiant floor/ceiling systems used for the district heating system and conventional building heating distribution components, were excluded from the analysis.

- Conveyance of recycled water within buildings was excluded from the study.
- Sludge management and gaseous operational emissions for individual components were excluded from this study.
- The end-of-life phase was not considered, as impact contributions have been found to be minimal relative to the construction and operational phases for the technologies used (Bartolozzi et al., 2017; Kobayashi et al., 2020).

3.3. Sensitivity Analysis

According to section 4.4.4.1 of ISO 14044 (ISO, 2006) (ISO, 2006), additional uncertainty and sensitivity analyses may be needed to help distinguish whether significant differences are present, to identify negligible LCI results, or to guide the iterative LCIA process. These choices are based on the accuracy and detail needed to fulfil the goal and scope of the LCA. Since this study expected that energy requirements such as electricity mixes play a large role in influencing LCA impacts, a sensitivity analysis was done to determine the variation in the results based on different types of electricity mix.

Operational requirements such as electricity production largely affects the environmental impact contributions of water management and heating systems (Jeong et al., 2018; Luickx et al., 2008). The 2018 Alberta electricity mix was used as the default alongside a 2040 projected electricity mix, and a hypothetical 100% renewable energy mix (Alberta Utilities Commission, 2020; National Energy Board, 2016). Specific electricity mixes used are shown in **Table 5**.

Table 5. Sensitivity analysis electricity mixes.

	AB2018	AB2040	Renewable
Hydro	2.3%	3.2%	3.2%
Wind	5%	10.1%	61.2%
Biomass/biogas	2.4	1.9%	18.4%
Solar	0.03%	0.8%	17.2%
Coal	42%	13.2%	
Natural gas	48%	70.4%	
Oil	0.4%	0.4%	

3.4. Life Cycle Inventory

3.4.1. Conventional Systems

Conventional space and water heating for semi-detached homes are modelled for the BAU scenario. Each household is individually equipped with a furnace and water heater, following an LCA study of a conventional residential home in Michigan, USA. Inventory data are shown in **Table 6**. The older dataset used for the space and water heating systems align with the development of the sewage heat recovery system of the time.

Table 6. Material and operational life cycle inventory data of conventional home heating components.

	Unit	**Value**	**Source**
TRANE XE-80 furnace			
Steel	$kg.PE^{-1}.y^{-1}$	4.39E-01	(Blanchard & Reppe, 1998)
Aluminium	$kg.PE^{-1}.y^{-1}$	3.33E-03	
Polyurethane foam	$kg.PE^{-1}.y^{-1}$	6.00E-03	
Glass	$kg.PE^{-1}.y^{-1}$	1.53E-02	
Paper	$kg.PE^{-1}.y^{-1}$	9.33E-03	
A.O. Smith 32000 BTU/HR input water heater			
Steel	$kg.PE^{-1}.y^{-1}$	1.11E+00	(Blanchard & Reppe, 1998)
Aluminium	$kg.PE^{-1}.y^{-1}$	2.00E-02	
Plastic	$kg.PE^{-1}.y^{-1}$	1.11E-02	
Polyurethane foam	$kg.PE^{-1}.y^{-1}$	1.11E-02	
Glass	$kg.PE^{-1}.y^{-1}$	5.11E-02	
Operational requirements			
Electricity	$kWh.PE^{-1}.y^{-1}$	1.35E+02	(Blanchard & Reppe, 1998)
Natural gas	$GJ.PE^{-1}.y^{-1}$	9.42E+00	

The conventional wastewater treatment system used in the Business-As-Usual (BAU) scenario includes primary treatment, biological treatment, and ultraviolet disinfection based on the existing local wastewater treatment plant (EPCOR, 2020b). The ecoinvent dataset was used for construction and demolition of the plant (Wernet et al., 2016). Chemical and operational inputs are shown in **Table 7**.

Table 7. Conventional wastewater treatment chemical and operational inventory.

	Unit	**Value**
Chemical components		
Alum	$kg.PE^{-1}.y^{-1}$	2.91E-01
Polymer	$kg.PE^{-1}.y^{-1}$	1.14E-02
Bleach	$L.PE^{-1}.y^{-1}$	5.47E-02
Caustic	$kg.PE^{-1}.y^{-1}$	3.29E-02
Operational energy		
Natural gas	GJ/L treated WW	5.1714E-07
Electricity	kWh/L treated WW	4.9823E-04

The construction and demolition of the conventional water treatment system in this study is from the ecoinvent database (Wernet et al., 2016). Operational requirements for the production and distribution of tap water were estimated from the averages of the 2017 and 2018 annual waterworks report of the local tap water supplier (EPCOR, 2020c). To calculate the appropriate impact values of the associated treatment systems, the operational scale of the system must be identified and matched with an appropriate unit to enter on OpenLCA. For example, tap water production in the software is associated the input of ecoinvent's water works flow for a certain volume capacity per year. In this case, ecoinvent's water works capacity of 6.23E10 L/year capacity per unit would need to be scaled to the capacity of the local water treatment system, which is 1.35827E10 L/year. Two units of ecoinvent's water works (capacity 6.23E10 L/year) produces 1.254E11 L/year, which is roughly below the amount of the local water treatment system's capacity. The number of people to be served by such services should be known to convert the input value into the functional unit of the study. The number of people served by the local water treatment system is 1212447 PE, which would equate to 112027.1649 L/PE/year, knowing the annual capacity of that treatment system. The input amount of people calculated per two units per year, as per the functional unit, is the capacity of 2 ecoinvent water works units (1.254E11 L) divided by the capacity served by the local water treatment plant (112027.1649

L/PE/year), resulting in 1119371.361 PE. The amount of units, the PE served, and the lifetime of the system can then be used as the input amount of the ecoinvent water works flow in the OpenLCA process, which is 2 units / 1119371.361 PE / 50 years. The same calculation was done for the wastewater treatment facility construction, of which the ecoinvent wastewater treatment facility (capacity 4.7E10 L/year) was used. The inventory data used for these processes are shown on **Table 8** based on per volume of water produced as varying water volumes were modelled.

Table 8. Life cycle inventory data of conventional tap water production.

Material	**Unit**	**Value**	**Source**
Aluminium sulfate	$mg.L^{-1}$	44.47	(EPCOR, 2018)
Filter polymer - Magnafloc LT 2AG	$mg.L^{-1}$	0.273	
Carbon chemical	$mg.L^{-1}$	61.93	
Sodium hypochlorite	$mg.L^{-1}$	3.25	
Aqua ammonia	$mg.L^{-1}$	0.565	
Caustic soda	$mg.L^{-1}$	8.8	
Fluoride	$mg.L^{-1}$	0.725	
Sodium bisulfite	$mg.L^{-1}$	21.85	
Energy usage			
Energy consumption for treatment and pumpage	$kWh.L^{-1}$	6.66E-04	(EPCOR, 2018)
Gas consumption for treatment and pump stations	$GJ.L^{-1}$	7.66E-07	

3.4.2. District Energy System and Sewage Heat Recovery

This study aimed to optimize the resource recovery potential of combined municipal wastewater by recovering heat energy and treating the wastewater at a community-scale for various water reuse purposes. The heat recovery system used for this study was adapted from a sewer heat exchange system in the City of Vancouver managed by the Southeast False Creek Neighbourhood Energy Utility (SFCNEU) (City of Vancouver, 2020). The SFCNEU system recycles waste heat captured from sewage and wastewater to provide heating and hot water for buildings. Of the energy requirements of the district heating system, 70% is supplied from sewage heat recovery (320% efficiency) and 30% is supplied from boilers (efficiency of 83%). Thermal distribution loss accounted only for 3%, with 2.5% ancillary on electrical. The inventory data used for this study is shown in **Table 9**.

Table 9. Southeast False Creek system material inventory data for the sewer heat recovery and district heating system.

	Unit	**Value**
Boiler plant		
Stainless steel	$kg.PE^{-1}.y^{-1}$	6.36E-02
Carbon steel	$kg.PE^{-1}.y^{-1}$	1.12E-02
Cast iron	$kg.PE^{-1}.y^{-1}$	2.12E-03
Bronze	$kg.PE^{-1}.y^{-1}$	9.07E-05
District heat		
Carbon steel	$kg.PE^{-1}.y^{-1}$	1.53E-02
Cast iron	$kg.PE^{-1}.y^{-1}$	3.00E-03
Bronze	$kg.PE^{-1}.y^{-1}$	3.33E-04
Sewage heat recovery		
Stainless steel	$kg.PE^{-1}.y^{-1}$	5.67E-02
Carbon steel	$kg.PE^{-1}.y^{-1}$	5.67E-02
Cast iron	$kg.PE^{-1}.y^{-1}$	1.65E-02
Bronze	$kg.PE^{-1}.y^{-1}$	6.05E-05
Sewage wet well		
Stainless steel	$kg.PE^{-1}.y^{-1}$	9.13E-04
Sewage pump station		
Cast iron	$kg.PE^{-1}.y^{-1}$	2.21E-03
Stainless steel	$kg.PE^{-1}.y^{-1}$	5.17E-03
Plant ventilation and odour control [a]		

Galvanized steel	$kg.PE^{-1}.y^{-1}$	4.25E-03
Stainless steel	$kg.PE^{-1}.y^{-1}$	7.94E-03
Cast iron	$kg.PE^{-1}.y^{-1}$	5.60E-04
Bronze	$kg.PE^{-1}.y^{-1}$	9.37E-05
Distribution pipe system [b]		
Steel	$kg.PE^{-1}.y^{-1}$	1.64E-01
Polyurethane foam	$kg.PE^{-1}.y^{-1}$	2.75E-05
Excavation	$m^3.PE^{-1}.y^{-1}$	9.10E-03
Operational requirements [c]		
Electricity	$kWh.PE^{-1}.y^{-1}$	3.71E+02
Natural gas	$GJ.PE^{-1}.y^{-1}$	2.65E-01

N/I: Not included
[a] Plant ventilation and odour control was limited to the wet well odour control system, chilled water pumps, heating coil pumps, and hot water tanks.
[b] Per unit equivalent of the distribution pipe system is based on the South East False Creek system and the region being serviced. HDPE pipe casing was not included in the analysis.
[c] Operational requirements are collected from the South East False Creek system and the region being serviced. As operational energy varies annually, an annual average of 10 years of operation was considered for this study. Sewage heat recovery for this system provides approximately 70% of energy requirements for district heating provision and the remaining 30% from gas boilers as of 2019.

Sewage for the heat recovery component is first screened and pumped into a central heat pump at 25˚C and returns to the sewage pump station at 20˚C. The heated refrigerant is upgraded using a compressor with a coefficient of performance of 3.5. Thermal energy is then transferred back into the district heating distribution system with an outgoing water temperature of 65˚C. A back-up system consisting of a gas-fired peaking boiler is used. The SEFC NEU system provides 3 megawatts (MW) of baseload capacity – requiring electricity for the heat pumps but yields 3.2 times the energy output (Lee, 2015). An additional 16 MW of natural gas capacity is provided for back-up and peak capacity needs. Space heating for the hypothetical district energy system is based on hydronic radiant floor/ceiling systems (City of Edmonton, 2017b). The design of the Vancouver district heating system is based on multi-unit buildings with lower expected energy consumption per household in comparison to detached single family home designs used for the baseline conventional scenario (City of Vancouver, 2020).

The chosen study location was inspired by the development of Blatchford community in Edmonton. The community was a general reference case for the scale of feasibility within the City of Edmonton. The concept of Blatchford as an infill development or redeveloping an area that was previously an airport is to create the first large scale net zero and carbon neutral community in Canada. Blatchford aims to have a District Energy Sharing System (DESS) composed of a centralized heating and cooling distribution system for various building stocks in the community. A geoexchange field is expected to harness shallow geothermal energy using 570 boreholes at a depth of 150 m. Similar to a *geothermal* system, a *geoexchange* field takes advantage of constant shallow underground temperatures to allow thermal energy transfer and storage for both heating and cooling (City of Edmonton, 2019). Sewage heat recovery in the case of Blatchford considers various options for the components of heat exchange technology, screening technology, and lift station pumping technology. A sewer trunk main is to be used for wastewater extraction, located at a depth of approximately 17 m, with a lift station designed for approximately 20 m deep. The Blatchford area of 536 acres (2 169 115 m^2) aims to house approximately 30,000 residents, as is designed for the study done here.

Average off-site sewer flows at the proposed connection location for the sewage heat recovery system are 500 L/s. This flow of sewage is greater than that of the SEFC NEU system, which typically aims to function at a constant flow of between 100 to 120 L/s. The estimated sewer temperature is 9.4 – 18.5˚C for the Blatchford development and approximately 20˚C (+/- 2˚C) for the SEFC NEU system. The heat pump technology uses a small amount of electricity to upgrade the low-grade thermal energy of wastewater.

3.4.3. Membrane Bioreactor

This study used membrane bioreactors (MBRs) to effectively treat municipal wastewater for various water reuses after the sewage heat recovery process. As the first stage of the wastewater had already been screened (1-3 mm capacity) through, prior to the heat recovery unit, influent is passed through directly into containers containing ultrafiltration membrane cassettes with porous membranes typically consisting of cellulose or other polymer materials (Cascadia Green Building Council, 2011; Jeong et al., 2018). MBRs have the advantage of producing high quality effluent while minimizing footprint, but at the cost of greater energy demands and greater operator attention (Cashman et al., 2018; Zenon, 2006). Observed MBR energy consumption data varies from study to study due to different capacities and technology development. The MBR operational energy used here aligns with the ranges of energy consumption values from various full-scale MBR installations treating mainly municipal wastewater in the Netherlands

(0.4-2.4 kWh/m^3) (Krzeminski et al., 2012) and is an overestimated value compared to AeMBR energy consumption estimates of different scales from the Cascadia Green Building Council, 2011 study, understanding that a drawback of MBR systems is their higher energy requirements. The inventory data used for the study is shown in **Table 10**.

Table 10. Life cycle inventory data for MBR system.

	Material	**Unit**	**Value**
Pre-treatment fine screen	Steel	$kg.m^{-3}.y^{-1}$	1.97E-02
Concrete pad	Concrete	$m^3.m^{-3}.y^{-1}$	2.99E-02
Steel container	Steel	$kg.m^{-3}.y^{-1}$	9.69E-03
Mixer	Steel	$kg.m^{-3}.y^{-1}$	2.17E-03
Aeration system piping	PVC	$kg.m^{-3}.y^{-1}$	9.32E-05
Aeration system rubber piping	Rubber-silicon based	$kg.m^{-3}.y^{-1}$	3.94E-04
Pump	Steel	$kg.m^{-3}.y^{-1}$	1.05E-03
MBR reactor steel housing	Steel	$kg.m^{-3}.y^{-1}$	1.09E-03
Membranes	Polyvinylidene fluoride [b]	$kg.m^{-3}.y^{-1}$	3.28E-04
Recycle pump	Steel	$kg.m^{-3}.y^{-1}$	7.22E-04
Air blower	Cast iron	$kg.m^{-3}.y^{-1}$	1.03E-03
Controls/portable instruments	Polyester	$kg.m^{-3}.y^{-1}$	6.57E-05
Operational requirements			
Membrane cleaning	Sodium hypochlorite	$kg.m^{-3}.y^{-1}$	4.90E-02
Electricity		$kWh.m^{-3}$	1.96

[a] Inventory data sourced from literature and is based on per volume of water produced (Cascadia Green Building Council, 2011). The excavation process was not included as it is considered to have negligible impacts for the associated scale.
[b] Polyvinyl fluoride was used instead of polyvinylidene fluoride for this study (Kobayashi et al., 2020).

3.4.4. Recycled Water Distribution Inventory

Local guidelines and previous research suggested a minimum diameter of 150 mm for main pipes and 20 mm for service pipes to be used for water distribution (City of Edmonton, 2017a). Header PVC pipes were estimated to be more than 7.11 mm thick with an outside diameter of 168 mm and an estimated weight of 5.25 kg/m. Branch pipes were estimated to be more than 2.87 mm thick with an outside diameter of 26.7 mm and an assumed weight of 0.313 kg/m. Pipe lengths are shown in **Table 11**. Pumping energy for the distribution pipes were estimated using EPANET 2 (Rossman, 2000). The recycled water distribution system shown in **Figure 3** was used so simulate pumping energy based on a central pump leading to 5 junctions and 5 tanks, with an average efficiency of 75%.

Table 11. Recycled water distribution inventory

	Material	**Unit**	**Value**
Service line [a]	PVC	$kg.PE^{-1}.y^{-1}$	1.13E-02
Main pipe [b]	PVC	$kg.PE^{-1}.y^{-1}$	6.65E-03
Pumps	Cast iron	$kg.PE^{-1}.y^{-1}$	1.09E-04
	Bronze impeller	$kg.PE^{-1}.y^{-1}$	1.21E-05
Operation			
Electricity		$kWh.m^{-3}$	6.18E-02

[a] Estimated 108 400 m length of service lines.
[b] Estimated 3 800 m of main pipelines.

3.4.5. Lifespan

The lifespans of the associated components used for this study has been estimated from previous studies and manufacturer sources and are shown in **Table 12**. Lifespan values will vary according to various sources. For the purpose of the configuration of the evaluated technology, the Canadian context is taken into account for the sewage heat recovery system. The lifespan of conventional heat systems has been sourced from an LCA study that has technology that is still widely available in the past decade, aligning with the development and application of the sewage heat recovery system from Vancouver. Conventional wastewater treatment and water treatment plants, as well as MBR systems have been estimated using a U.S. EPA study that has uses a widely known estimated lifespans of the systems based on previous research and collected data (Cascadia Green Building Council, 2011). As new lifespan data is released on these different technologies and processes, lifespans may be easily modified in OpenLCA to suit the new configurations, with modifications in the construction, operational, and other phases of the studied systems accordingly.

Table 12. Lifespan of LCA components.

	Unit	**Value**	**Source**
Conventional systems			
Conventional wastewater treatment plant	years	50	(Cascadia Green Building Council, 2011)
Conventional water treatment plant	years	50	(Cascadia Green Building Council, 2011)
Conventional home heating components (gas furnace and water heater)	years	15-50	(Blanchard & Reppe, 1998; Vignali, 2017)
District energy system			
Sewage heat recovery and district energy	years	30	(Kerr Wood Leidal Associates LTD., 2013)
Distribution pipes	years	30	(Fröling et al., 2004; LOGSTOR, 2020)
Sewage wet well	years	100	Assumed lifespan of steel gates before disposal or recycling.
Sewage pump station, heat pumps, water pumps	years	15	(Hydraulic Institute et al., 2001)

Boilers	years	15	(Vignali, 2017)
Wet well odour control	years	35	Contacted manufacturer
Membrane bioreactor system			
Screen (pretreatment)	years	50	(Cascadia Green Building Council, 2011)
MBR reactor	years	50	
Membrane	years	10	
Pump	years	10	
Mixer	years	10	
Air blower	years	15	
Controls	years	25	

3.5. Software

The LCA calculations were performed with the OpenLCA program similarly used by previous assessments for wastewater treatment technologies (Cashman & Mosley, 2016; Kobayashi et al., 2020). The software is a free open source software to conduct sustainability and life cycle assessments. Using an accessible software such as OpenLCA enables facility of replication and reconfiguration of the study done here. OpenLCA has been used extensively by different institutions for research purposes in water and wastewater sectors (Cascadia Green Building Council, 2011; Vergara-araya et al., 2020). Additionally, the source code of OpenLCA is completely open for developers, enabling transparency and customizability of calculation assumptions.

OpenLCA functions on 4 main database elements to model and compare product systems: Flows, processes, product systems, and projects. Flows are defined as the product, material, or energy inputs and outputs of processes in the product system under study, of which OpenLCA distinguishes three types: elementary flows, product flows, and waste flows. Elementary flows are associated with the direct input and output emissions, material, or energy of the environment. Product flows are associated with the material or energy exchanged between different processes of the product system. Waste flows are material or energy leaving the product system. Each flow is defined by a unit reference flow property (i.e. mass, volume, area, etc.). This study utilizes elementary and product flows to represent material and energy inputs and outputs for the heat recovery and wastewater treatment systems being investigated. Processes are defined as the sets of interacting activities that transform inputs into outputs, of which OpenLCA distinguishes two types: Unit processes and system processes. Unit processes are the smallest unit analyzed for which input and output data are quantified. System processes are units for which input and output data are aggregated. Product systems contain all processes under study which may contain one process or a network of multiple processes and is defined by the reference process.

For the case of this study, individual unit processes have been manually inputted and defined based on the different components of community-based sewage heat recovery and wastewater treatment systems. Three main categories were defined as: 1) wastewater treatment, 2) residential heating, and 3) water treatment. Each of these categories have multiple components, depending on which scenario is being evaluated. The category of wastewater treatment has the additional categories for *Conventional WWT* and *MBR for Water Reuse*. The unit process of Conventional WWT is then composed of the various product flows involved in conventional wastewater treatment processes, such as energy requirements and chemical consumption. A combination of flow products makes up a product system, for instance, a scenario modelling a conventional or business-as-usual case would include product flows of the treatment technologies and components for conventional systems that are being evaluated.

3.5.1. Organization of Product Systems, Processes, and Flows

Output data were collected by exporting analysis results of product systems to Excel documents. Specific impact analysis results were then extracted by impact category based on the different process results associated with each product system. By default, exported results include the 9 impact indicators that the TRACI method provides. Cumulative impact values are listed and combined according to the different representations of the data, for instance, if specific impact values associated with the operational component of the system, those values are isolated to be able to make comparisons to other scenarios.

For each system process, input parameters have been defined and assigned to easily manipulate changes of input variables that should be modified. For instance, multiple values of water reuse and energy consumption are used, so dependent parameter formulas should be defined so that multiple modifications in input variables can be considered. For instance, three dependent parameters have been defined within the conventional WWT process:

p_general_electricity = (p_gbwwtp_electricity) * (p_water_consumption)

p_natural_gas = (p_gbwwtp_natgas) * (p_water_consumption)

p_water_consumption = (p_wateruse_IR) / (p_PE)

Input parameters that have been defined and used in the above dependent parameter formulas are p_gbwwtp_electricity (conventional local WWTP electricity rate, kWh/m^3), p_gbwwtp_natgas (conventional local WWTP natural gas use rate, GJ/m^3) , p_wateruse_IR (water use rate for irrigation, m^3/yr), and p_PE (population equivalent used). Different input parameters then have been defined based on factors like different water use rates, which in turn alter water consumption values, and electricity and natural gas usage.

Dependent parameters have been defined for the process groups of wastewater treatment, water treatment, and residential heating for the study. The definition and organization of dependent parameters may alternatively be done through spreadsheets, followed by manually inputting calculated values on the OpenLCA software.

This study largely utilized the global market to represent the average amount of transport activity between producers and consumers of the reference product. Global market datasets are the consumption mixes of a certain product in a global context, which takes into account production volumes of a product and its global market share to calculate the estimated environmental contributions from a global perspective. While an LCA would ideally be a snapshot of a specific region, the available data for the technologies being evaluated has been sourced from many different locations. Thus, the global market reference of the ecoinvent database is used to take into account average transport impacts of the many components of the studied systems. The amount of transport in the market may be calculated through a search of the reference product from the ecoquery wherein the required amounts and units are indicated.

3.5.2. Formatting of Values to Avoid Errors in Calculations

The values for the study must be formatted appropriately to minimize data entry errors. As OpenLCA exports data into Excel files, transferring data tables and reading the appropriate rows and columns require close attention during iterations and revisions. Here, Excel spreadsheets were colour coded based on the different impact indicators (GWP, EUP, and HHCP), as well as for the different categories being studies, such as construction and operation phases. In addition to Excel outputs, OpenLCA enables the user to see the total impact analysis results as well as the contributions of different processes according to different impact categories. This can be referred to when looking at the output results from Excel to be assured that the values are in their proper categories. As LCA is naturally an iterative process, repetitive reviewing of the contribution and individual values of different system components is important in the proper identification of results.

3.6. Impact Assessment Method: Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)

The three impact indicators used for the study are global warming potential (GWP), eutrophication potential (EUP), and human health carcinogenic potential (HHCP) from the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) (Jeong et al., 2018; Kobayashi et al., 2020; Rahman et al., 2016). These impact indicators have been used in water management related LCAs specifically for North American contexts (Dong et al., 2016); alternatives include to ReCiPe, CML, Eco-indicator, which are other widely used LCA method that have been applied for many European case studies, likely since these indicators were developed in Europe. Ecotoxicity and human toxicity impact factors have been found to have the greatest variations between different LCIA methods compared indicators related to climate change, acidification, ozone depletion, and energy resources (Dong et al., 2016).

This LCA study uses TRACI as the characterization factors to quantify the potential impacts that inputs and releases have on specific impact categories in common equivalence units (Bare, 2012). The characterization factors for the associated media are listed:

- Ozone Depletion (Air),
- Global Climate / Global Warming Potential (Air),
- Acidification (Air, Water),
- Eutrophication (Air, Water),
- Smog Formation (Air),
- Human Health Impacts (Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil), and
- Ecotoxicity (Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil).

As this study is based on the Canadian context and therefore uses TRACI instead of other impact assessment methods due to its applicability to the United States. The impact category of climate change is indicated as global warming potential or GWP and is defined as the calculation of the potency of greenhouse gases relative to CO_2 (Bare, 2012). Eutrophication or EUP as defined by the EPA is the enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass (Bare, 2012).

4. Results

This section firstly includes results related to the early stage processing of the data, followed by the comparison of different water reuse scenarios and different system components. The findings of the sensitivity analysis are then presented.

4.1. Early Stages of Data Processing

One component of data validation is to ensure that there is no significant difference between data using the ecoinvent database and the local water treatment plant. A comparison between these two sets of results was compared for the three scenarios of BAU, DESS, and DESS+MBR based all TRACI impact indicators. By comparing both local data to the ecoinvent database data specifically for the water works and local wastewater treatment plant processes, it can be observed that the values do not vary significantly from one another (**Table 13**). In this case, the ecoinvent process was used alongside major chemical requirements from the local water treatment plant to receive the most accurate snapshot of the study scenarios.

Initial modelling considered all 7 TRACI impact indicator categories, to have a broader understanding of the impact contributions based on the three base scenarios of BAU, DES, and DES+MBR (using irrigation and toilet flush water reuse volumes). The LCA results were represented on a percent distribution shown on **Figure 4**. The results show that the BAU scenario dominated for the impact environmental impact indicators of ozone depletion and global warming potential, and the human health indicators of non-carcinogenics and carcinogenics. The DES+MBR scenario led on the impact indicators of acidification, eutrophication, photochemical oxidation, and respiratory effects.

Table 13. Comparison between ecoinvent water works plant process and local treatment plant process.

	BAU LOCAL	DES LOCAL	DES+MBR LOCAL	BAU ECOINVENT	DES ECOINVENT	DES+MBR ECOINVENT
Acidification (moles of H^+-Eq)	7.85E+01	1.61E+02	1.66E+02	7.80E+01	1.61E+02	1.67E+02
Ecotoxicity (kg 2,4-D-Eq)	1.13E+02	2.34E+02	2.28E+02	1.12E+02	2.33E+02	2.29E+02
Eutrophication (kg N-Eq)	4.70E-02	7.60E-02	8.41E-02	4.67E-02	7.57E-02	8.45E-02
Global warming (kg CO_2-Eq)	8.47E+02	6.42E+02	6.38E+02	8.46E+02	6.40E+02	6.39E+02
Ozone depletion (kg CFC-11-Eq)	9.59E-05	8.87E-05	9.08E-05	9.52E-05	8.80E-05	9.14E-05
Photochemical oxidation (kg NO_x-Eq)	7.50E-01	1.03E+00	1.17E+00	7.46E-01	1.03E+00	1.17E+00
Carcinogenics (kg benzene-Eq)	5.71E-01	9.87E-01	9.26E-01	5.65E-01	9.81E-01	9.32E-01
Non-carcinogenics (kg toluene-Eq)	1.18E+03	1.64E+03	1.51E+03	1.16E+03	1.63E+03	1.52E+03
Respiratory effects (kg $PM_{2.5}$-Eq)	3.21E-01	5.65E-01	5.82E-01	3.18E-01	5.62E-01	5.85E-01

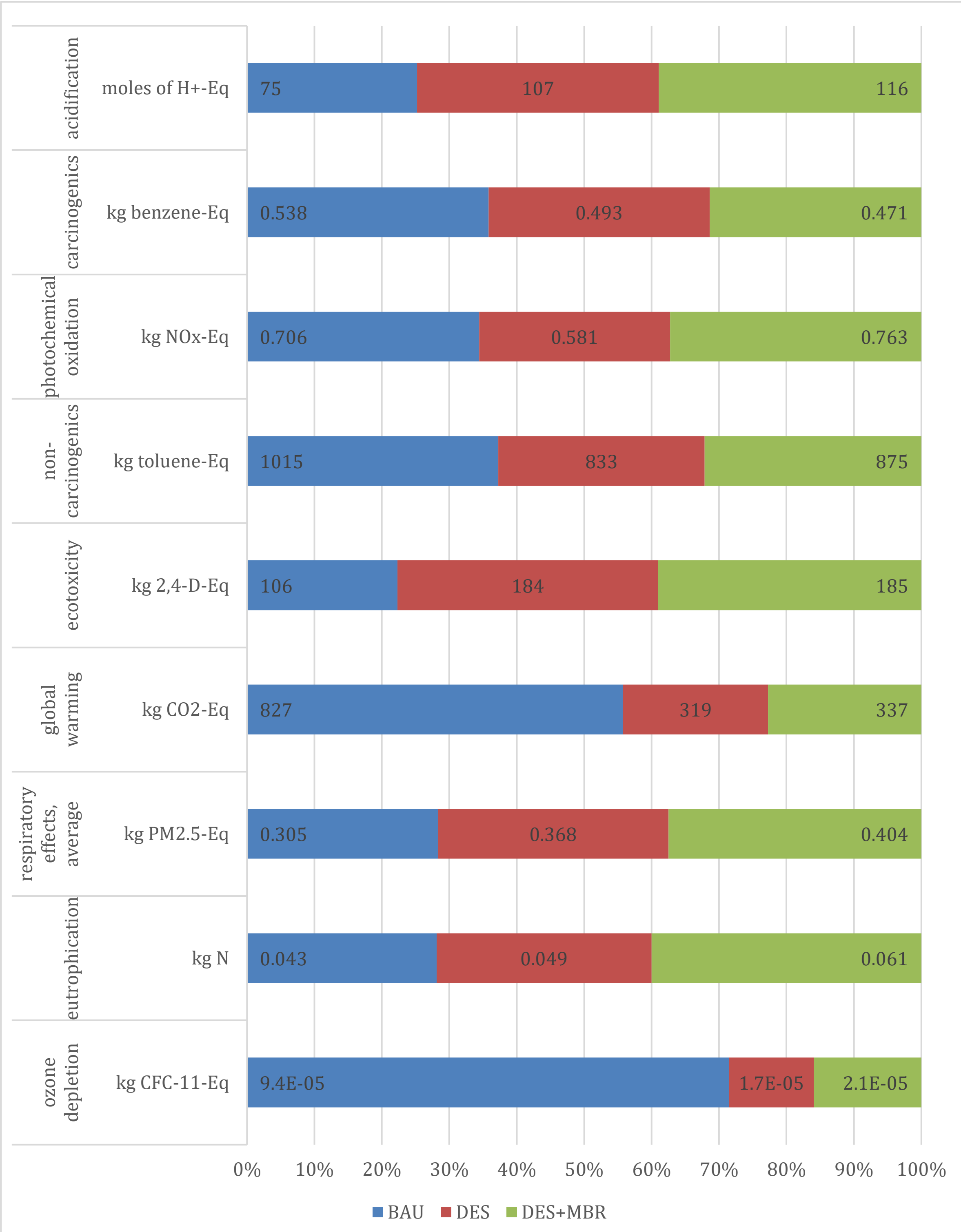

Figure 4. Validation results for the comparative LCA of an integrated sewage heat recovery and water reuse system. BAU: Business-as-Usual; DES: District Energy System; MBR: Membrane Biological Reactor.

4.2. Comparison of Different Water Reuse Scenarios

In general, the BAU scenario resulted in the greatest GWP values, was similar between BAU and DES for EUP and HHCP, and the DES+MBR impacted the least across the three parameters (**Figure 5**). Irrigation as a choice of water use (101 835 $m^3.y^{-1}$) for the community showed little to no difference for the EUP and HHCP indicators for the DES+MBR scenario. However, as water use volumes increase to include toilet flushing and clothes washing, greater environmental savings were estimated when community-based wastewater treatment and water reuse systems were applied, based on the significant increase in EUP and HHCP values for the BAU and DES systems as water use volumes increase. The DES and BAU applications dominate for both the EUP and HHCP impact values, with EUP impacts showing the highest values for the DES systems, and HHCP impacts showing the highest values for the BAU systems.

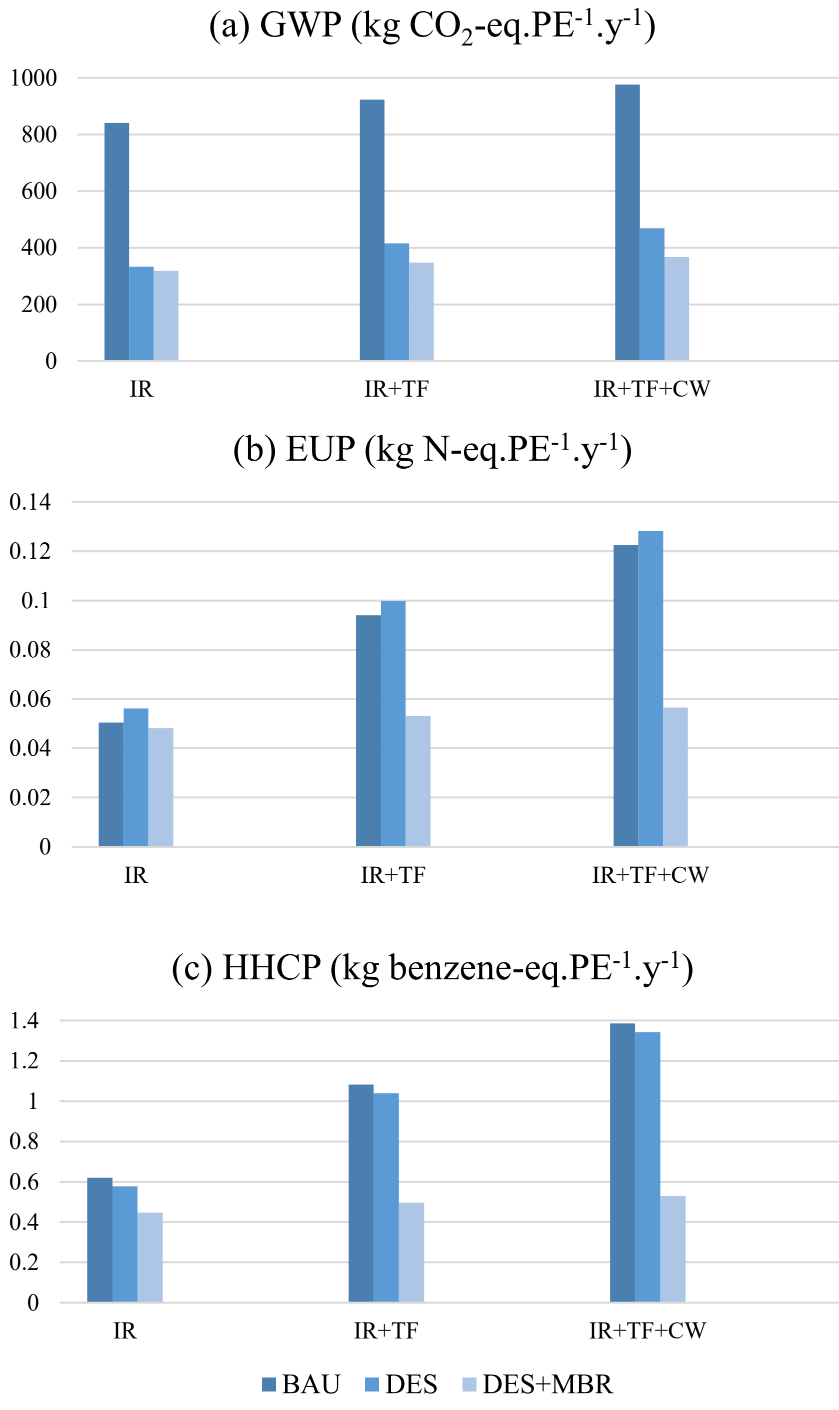

Figure 5. Comparison of Business-as-usual (BAU), District energy system (DES) and District energy system with membrane bioreactor treatment (DES+MBR) for impact categories: (**a**) Global warming potential (GWP), (**b**) Eutrophication potential (EUP), and (**c**) Human health – carcinogenic potential (HHCP) for different water reuse scenarios.

Relative to the combined impacts of water treatment, wastewater treatment, space and water heating, and MRB systems, the DES+MBR system exhibited the least variation in impacts as water use volumes increase. Overall, impact contributions from the operational phase dominated over the construction phase for GWP (>98%), EUP (>96%), and HHCP (>85%) (**Table 14**). Construction phase contributions were generally in the range of 1-15% for each impact category. BAU scenarios tended to have greater contributions associated with the construction phase compared to DES and DES+MBR scenarios. GWP, EUP, and HHCP impacts from water reuse savings expectedly increased from the lowest water use volume to the highest for the DES+MBR applications.

Table 14. Impact contributions of construction and operational phases of system components for BAU, DES, and DES+MBR applications under various water reuse options.

		BAU			DES			DES+MBR		
		IR	IR+TF	IR+TF+CW	IR	IR+TF	IR+TF+CW	IR	IR+TF	IR+TF+CW
GWP (kg CO_2-eq.PE^{-1}.y^{-1})										
Water Treatment System	CON	6.71×10^{-1}	6.75×10^{-1}	6.78×10^{-1}	6.71×10^{-1}	6.75×10^{-1}	6.78×10^{-1}	---	---	---
	OPR	1.07	7.29	1.14×10^{1}	1.07	7.29	1.14×10^{1}	---	---	---
Space and Water Heating System	CON	2.86	2.86	2.86	5.73×10^{-1}	5.73×10^{-1}	$5.73x^{-1}$	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}
	OPR	8.17×10^{2}	8.17×10^{2}	8.17×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}
Wastewater Treatment System	CON	5.85	5.85	5.85	5.85	5.85	5.85	---	---	---
	OPR	1.30×10^{1}	8.86×10^{1}	1.38×10^{2}	1.30×10^{1}	8.86×10^{1}	1.38×10^{2}	---	---	---
MBR System	CON	---	---	---	---	---	---	4.12×10^{-1}	2.59	4.02
	OPR	---	---	---	---	---	---	5.88	4×10^{1}	6.23×10^{1}
Water Reuse Savings		---	---	---	---	---	---	-1.07	-7.29	-1.14×10^{1}
Total		8.41×10^{2}	9.23×10^{2}	9.76×10^{2}	3.33×10^{2}	4.15×10^{2}	4.69×10^{2}	3.18×10^{2}	3.49×10^{2}	3.69×10^{2}
EUP (kg N-eq.PE^{-1}.y^{-1})										
Water Treatment System	CON	1.01×10^{-4}	1.02×10^{-4}	1.03×10^{-4}	1.01×10^{-4}	1.02×10^{-4}	1.03×10^{-4}	---	---	---
	OPR	1.80×10^{-4}	1.22×10^{-3}	1.91×10^{-3}	1.80×10^{-4}	1.22×10^{-3}	1.91×10^{-3}	---	---	---
Space and Water Heating System	CON	6.78×10^{-4}	6.78×10^{-4}	6.78×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}
	OPR	4.09×10^{-2}	4.09×10^{-2}	4.09×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}
Wastewater Treatment System	CON	1.32×10^{-3}	1.31×10^{-3}	1.32×10^{-3}	1.32×10^{-3}	1.31×10^{-3}	1.32×10^{-3}	---	---	---
	OPR	7.32×10^{-3}	4.98×10^{-2}	7.76×10^{-2}	7.32×10^{-3}	4.98×10^{-2}	7.76×10^{-2}	---	---	---
MBR System	CON	---	---	---	---	---	---	1.08×10^{-4}	6.82×10^{-4}	1.06×10^{-3}
	OPR	---	---	---	---	---	---	9.63×10^{-4}	6.55×10^{-3}	1.01×10^{-2}
Water Reuse Savings		---	---	---	---	---	---	-1.80×10^{-4}	-1.22×10^{-3}	-1.91×10^{-3}
Total		5.05×10^{-2}	9.40×10^{-2}	1.22×10^{-1}	5.62×10^{-2}	9.97×10^{-2}	1.28×10^{-1}	4.82×10^{-2}	5.35×10^{-2}	5.69×10^{-2}
HHCP (kg benzene-eq.PE^{-1}.y^{-1})										
Water Treatment System	CON	3.72×10^{-3}	3.74×10^{-3}	3.76×10^{-3}	3.72×10^{-3}	3.74×10^{-3}	3.76×10^{-3}	---	---	---
	OPR	3.17×10^{-3}	2.16×10^{-2}	3.37×10^{-2}	3.17×10^{-3}	2.16×10^{-2}	3.37×10^{-2}	---	---	---
Space and Water Heating System	CON	3.41×10^{-2}	3.41×10^{-2}	3.41×10^{-2}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}
	OPR	4.46×10^{-1}	4.46×10^{-1}	4.46×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}
Wastewater Treatment System	CON	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	---	---	---
	OPR	7.66×10^{-2}	5.21×10^{-1}	8.12×10^{-1}	7.66×10^{-2}	5.21×10^{-1}	8.12×10^{-1}	---	---	---
MBR System	CON	---	---	---	---	---	---	2.51×10^{-3}	1.67×10^{-2}	2.61×10^{-2}
	OPR	---	---	---	---	---	---	9.50×10^{-3}	6.46×10^{-2}	1.01×10^{-1}
Water Reuse Savings		---	---	---	---	---	---	-3.17×10^{-3}	-2.16×10^{-2}	-3.37×10^{-2}
Total		6.19×10^{-1}	1.08	1.39	5.77×10^{-1}	1.04	1.34	4.47×10^{-1}	4.99×10^{-1}	5.33×10^{-1}

CON: Construction; OPR: Operation; BAU: Business-as-Usual; DES: District Energy System; MBR: Membrane Biological Reactor; IR: Irrigation; TF: Toilet Flushing; CF: Clothes Washing

4.3. Comparison of the Different System Components

The major source of impact was contributed by space and water heating systems for all scenarios (67-98%), attributed to greater energy consumption relative to other processes like water treatment, wastewater treatment, and MBR systems (**Figure 6**). As expected, increasing volumes of water use correspondingly increased the contributions of wastewater treatment and MBR systems. However, the DES+MBR scenarios generally show a lower overall GWP contribution from wastewater treatment related processes using the MBR system, as opposed to the BAU and DES scenarios. While water treatment systems for the BAU and DES generally accounted for less than 3% of GWP contributions, avoiding this contribution in the DES+MBR scenario due to community-based wastewater treatment and reuse offered additional environmental savings.

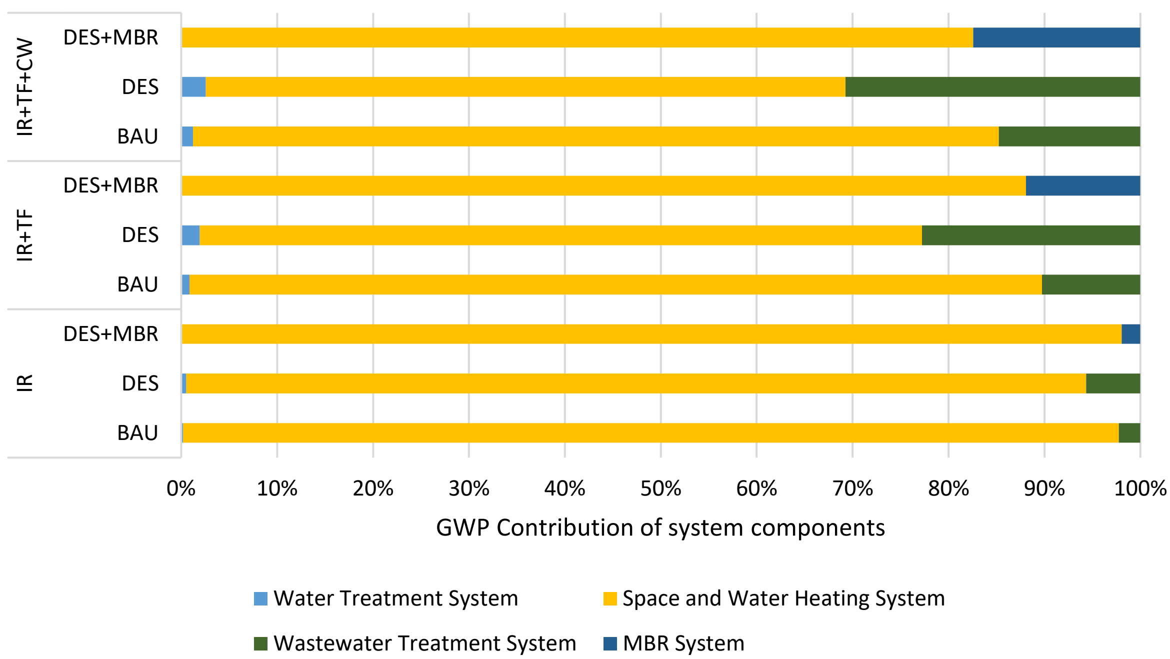

Figure 6. Global warming potential (GWP) impact contribution of system components for different study scenarios (business-as-usual (BAU), district energy system (DES), district energy system with membrane bioreactor (DES+MBR)) and water reuse options (irrigation (IR), toilet flushing (TF), clothes washing (CW)).

The impact categories of EUP and HHCP showed similar contributions across system components, with the exception of slightly lower EUP contribution for the space and water heating system (**Figure 7**), and a slightly higher HHCP contribution for water treatment (**Figure 8**). Larger EUP and HHCP impact contributions from the wastewater treatment systems were observed for DES and BAU, particularly as water reuse volumes increased across the options, attributable to increases in operational needs. All scenarios indicate lower impacts relative to the overall contributions for the MBR systems compared to traditional centralized wastewater treatment.

A lower proportion of GWP and HHCP impact from the space and water heating system for the DES scenarios was observed compared to the BAU scenarios. Slightly higher EUP contributions for the DES scenarios were attributed to natural gas requirements from the sewage heat recovery system to meet community district heating needs.

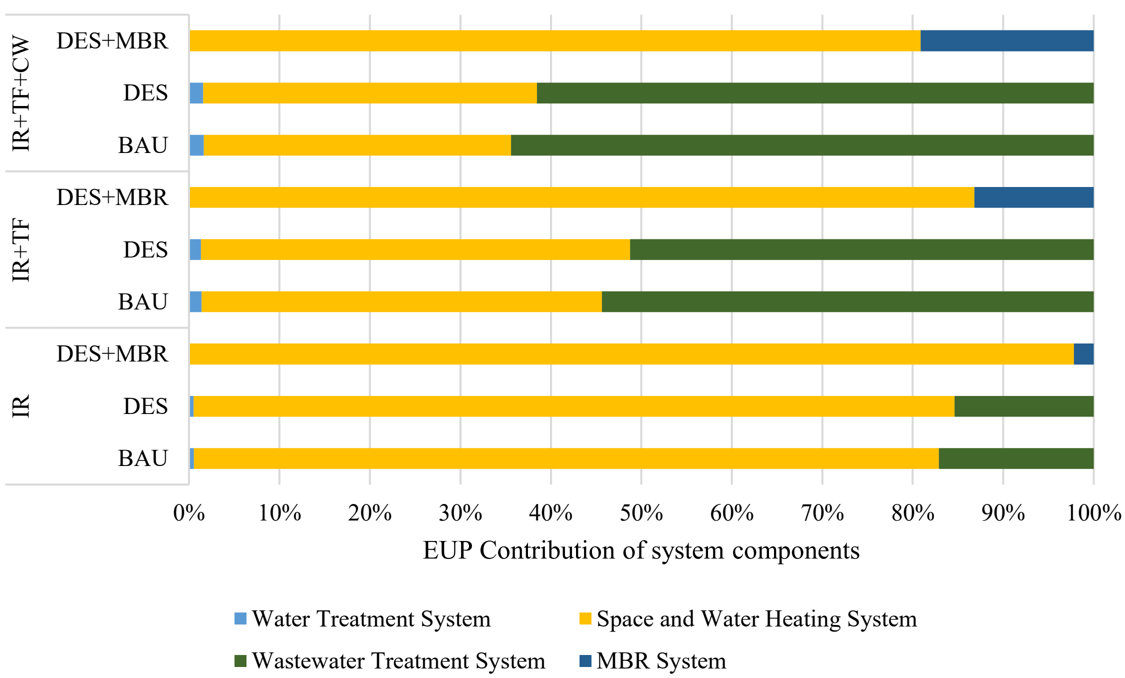

Figure 7. EUP impact contribution of system components for different study scenarios (business-as-usual (BAU), district energy system (DES), district energy system with membrane bioreactor (DES+MBR)) and water reuse options (irrigation (IR), toilet flushing (TF), clothes washing (CW)).

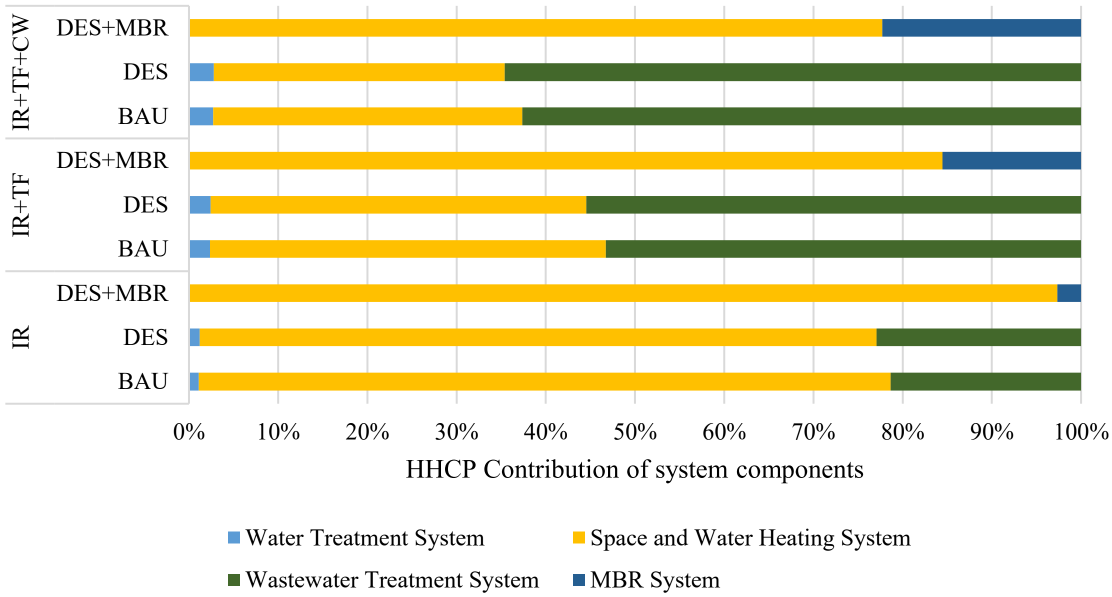

Figure 8. HHCP impact contribution of system components for different study scenarios (business-as-usual (BAU), district energy system (DES), district energy system with membrane bioreactor (DES+MBR)) and water reuse options (irrigation (IR), toilet flushing (TF), clothes washing (CW)).

4.4. Sensitivity Analysis – Alternative Electricity Mixes

GWP contributions were largely dominated by BAU scenarios and show lower impacts in the 2040 and renewable electricity mixes relative to the default (fossil fuel) electricity mix. Impacts increased as water reuse volumes increase across the different applications modelled (**Figure 9a**). However, even with the largest water reuse volume (IR+TF+CW), using a renewable electricity mix resulted in lower impact contributions than that of lowest water reuse volumes (IR) using either a 2018 or projected-2040 electricity mix.

A decreasing trend for HHCP was also observed for 2040 and renewable electricity mixes (**Figure 9c**). DES+MBR scenarios however, show > 50% decrease in HHCP compared to BAU and DES scenarios, particularly as water reuse volumes increased, as energy consumption from conventional water and wastewater treatment processes were avoided.

The renewable electricity mix showed larger EUP contributions for BAU, DES, and DES+MBR scenarios compared to 2018 and 2040 electricity mixes. As EUP generally increased when water reuse volumes increased, the DES+MBR scenarios remained lower for the 2018 and

2040 electricity mixes due to the reduction of water and wastewater treatment processes. The greater impacts associated with the renewable electricity mix is attributable to the 18.4% use of biomass/biogas compared to the 2018 and 2040 electricity mixes at 2.4% and 1.9%, respectively.

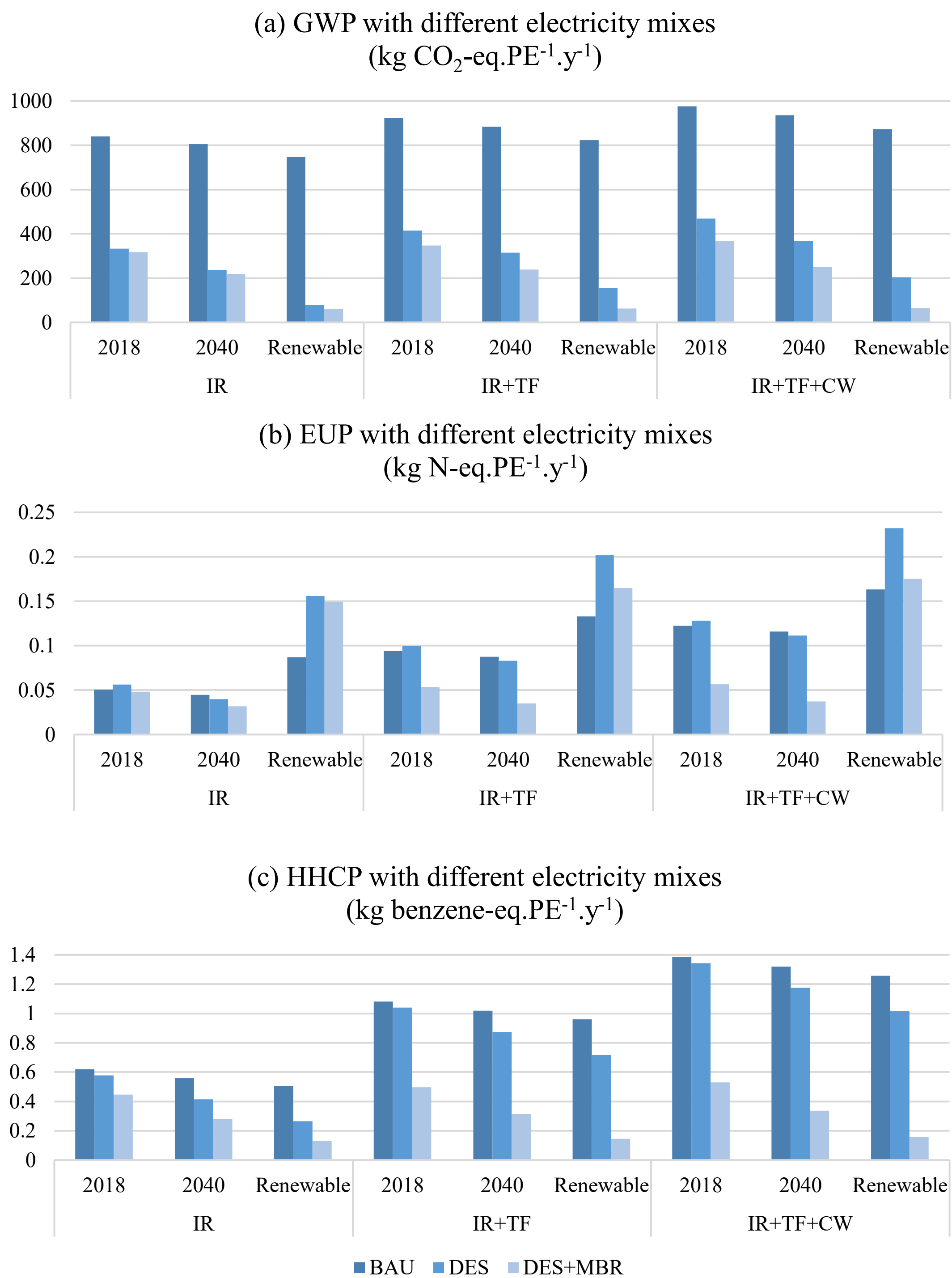

Figure 9. Impact categories (**a**) GWP, (**b**) EUP, and (**c**) HHCP for different electricity mixes across the three systems modelled (business-as-usual (BAU), district energy system (DES), district energy system with membrane bioreactor (DES+MBR)) and water reuse options (irrigation (IR), toilet flushing (TF), clothes washing (CW)).

5. Discussion

In striving for improved provision of urban water services, various options for hybrid centralized/distributed systems have been identified, some using novel technologies (Zodrow et al., 2017). However, most of these innovative solutions have not been considered economically feasible, and there are significant practical challenges in adapting them to major city centers (CWN, 2015; WSAA, 2019). Here, a modular approach to facilitate reconfiguration of water service infrastructure is presented. The core interest in the current study was the environmental impact of a transitional design whereby sewage heat recovery is used for district heating alongside community-based wastewater treatment for water reuse. Such transitional designs may facilitate more realistic applications of innovative technologies.

The results indicate that the use of a sewer-heat-recovery-based district heating system integrated with community-based wastewater treatment and water reuse can reduce environmental (GWP and EUP) and human health (HHCP) impacts by over half in comparison to conventional systems. This finding aligns with research investigating the environmental benefits of resource recovery from conventional wastewater treatment technologies (Cornejo et al., 2016), considering potable water use is avoided. However, it should be noted that the impacts of the wastewater treatment component explored here is only a small component of the cumulative impacts which included the residential heating systems, when looking at the DES+MBR systems, which was expected to maximize environmental performance. Since space and water heating systems comprise over 70% of the GWP for conventional systems, the focus on shifting to district-energy-based systems facilitates the initial step in optimizing environmental performance and sustainability for community structures. Based on the default electricity mix, the largest contributors to the environmental impact indicators of the study are electricity and natural gas consumption. Yet, even with a transition to renewable energy sources, DES and local water reuse options appear more advantageous than BAU systems (**Figure 9**).

Compared to the BAU scenarios, impacts for DES applications were reduced due to lower overall energy and chemical use. While the MBR system showed higher energy requirements compared to conventional wastewater treatment systems, overall impacts were still lower because of the lower chemical consumption (alum and polymer) associated with MBR and the avoidance of tap water production through water reuse. MBR-associated scenarios also achieved lower life cycle impacts for the construction phase compared to BAU, as previously noted

(Renou et al., 2008; Smith et al., 2014). Considering that the estimated energy consumption values used for the MBR applications in the study were slightly higher than the average electricity rates from previous systems, lower impact values would be expected with recent MBR developments and optimizations.

The sensitivity analysis showed that environmental and human health impacts are largely dictated by variations in the chosen electricity mixes. Greater EUP for the renewable electricity mix, for instance, was attributed to the higher use of biogas/biomass electricity production versus the conventional and projected electricity mixes. The EUP would otherwise be much lower using DES+MBR applications, due to lower overall impacts from the electricity mix.

Sewage-heat-recovery-based district heating systems can yield additional environmental savings with community-based wastewater treatment and water reuse, particularly when a greater volume of wastewater is utilized. Conventional wastewater and water treatment systems consistently demonstrated over 20% increases in EUP and HHCP contributions from IR to IR+TF and from IR+TF to IR+TF+CW, while the use of community-based MBR treatment showed consistently lower impacts in the three water reuse scenarios examined, making it a sustainably effective alternative to the use of conventional drinking water.

Water reuse applications for irrigation, toilet flushing, and clothes washing for the hypothetical community in the DES+MBR applications were consistently the most effective across the three impact categories examined. While studies have already shown the environmental favorability of district heating systems compared to conventional systems (Eriksson et al., 2007; Joelsson & Gustavsson, 2009), research in community-based wastewater treatment and reuse is at an early stage of development (Kobayashi et al., 2020). Other alternative treatment technologies for water reuse, such as phototreatment or the use of photoreactors for the disinfection step has also yielded environmental benefits despite construction and operational conditions of the reactors (Lutterbeck et al., 2017). The reduction in impacts from sewage-heat-recovery-based district heating systems can yield additional environmental savings with community-based wastewater treatment and water reuse, particularly when a greater volume of wastewater is used in the process.

Based on the minimum household greenhouse gas emissions per capita in Alberta which was estimated at 3.9-4.5 t in 2016 (Statistics Canada, 2019), a reduction of over 13% kg CO_2/PE/year can be achieved with the DES+MBR scenario under IR conditions compared to the BAU scenario, and at most, a 15.6% reduction can be achieved under IR+TF+CW water reuse conditions. While including MBR treatment to the DES scenario results in the largest reduction in GWP, a significant GWP reduction can already be achieved by changing from conventional home heating systems to a district energy system.

Overall, integrating water reuse in environmentally optimized solutions like district heating systems appears to facilitate thinking towards community-based approaches and more localized sustainability. As demonstrated here, current sewage systems can thus be utilized to decrease environmental impacts, while the shift towards decentralized systems may be planned for future growth/rebuilds accordingly.

5.1. Limitations

The heat recovery potential of urban wastewaters varies significantly between regions because of different environmental conditions and sewage characteristics (Cipolla & Maglionico, 2014; Vestberg, 2017). Changes in the structure of sewage systems, in addition to variations in peak water consumption, must be identified on a case-to-case basis to evaluate heat recovery potential. Sewage system qualities, such as temperature and flow are key parameters in determining the feasibility of a wastewater heat recovery system and can be further used to map potential thermal energy of sewage systems using modelling tools (Cipolla & Maglionico, 2014).

This study was limited to construction and operational phases and excluded direct operational emissions of individual system processes. Ideally, direct operational emissions for individual system processes may be applied as specific studies are done on different components of the study system. For instance, optimization studies to minimize operational emissions from pumping configurations, heat pump configurations, and wastewater treatment technologies may further identify influences on the environmental performance of the system.

Different perspectives of how to approach environmental savings should be considered, particularly when determining environmental offsets due to factors like avoiding potable water use. While the study included the avoidance of treated potable water, it should also be considered that other regions may use less energy-intensive sources of non-potable irrigation water, which can be considered for future studies (Cornejo et al., 2016).

Past research has noted that LCA of MBRs should be implemented for various operational conditions for environmental assessment and optimization purposes (Holloway et al., 2016;

Ioannou-Ttofa et al., 2016; Ribera-Pi et al., 2020). This study in part investigated changes in environmental impacts based on different electricity mixes, however further modifications may be possible by changing operational configurations of MBRs and other associated processes in the heat recovery and water conveyance systems.

While the LCA done here includes a sensitivity analysis using different electricity mixes which have been considered to have the greatest environmental implications based on the indicators used, many other parameters can be studied to further reduce or recognize uncertainties in an assessment. Recognizing technological and market factors in relation to integrated wastewater resource recovery systems

5.2. Future Research

5.2.1. Other Resource Recovery and Emerging Technologies

Increased methane production potential and chemical oxygen demand (COD) removal efficiency using anaerobic membrane bioreactors (AnMBR) for sewer mining may be studied to optimize the environmental performance of sustainable community-based systems (Ferrari et al., 2019), however, upflow anaerobic sludge blanket (UASB) technology may be more effective, due to the associated environmental impacts of AnMBR membrane fouling (Xu et al., 2018). Various other technologies based on circular thinking may be modelled to further improve the environmental performance of sanitation options, such as nutrient recovery (Kjerstadius et al., 2015; Yee et al., 2019), biogas production from urban organic waste (Gao et al., 2020; L. Zhang et al., 2019) and blackwater (Gao, Zhang, Florentino, et al., 2019; Gao, Zhang, Guo, et al., 2019; Thibodeau et al., 2014; Zhou et al., 2020), and water reuse from source-diverted greywater (Zhou, Li, et al., 2020).

Other renewable energy sources, such as geothermal, can also be considered for a district heating system (Bloomquist, 2003), such as that of the planned Blatchford development in Edmonton, Alberta (City of Edmonton, 2019). The development aims to use geothermal and sewage heat recovery for its district energy system. This study provides the framework to evaluate such systems before and after full-scale construction and operation is complete to better understand the applicability of such technologies in other similar regions and conditions.

Water and energy conservation can be improved with UV-LED disinfection systems (Close et al., 2006; Francy et al., 2012), an alternative to the chlorine disinfection techniques that form the basis of conventional tap water production systems. While there are benefits of using chlorine disinfection, such as the provision of residuals in the water distribution system (Haas, 1999), more effective controls may be achieved using UV technologies (Das, 2002; Francy et al., 2012). Additionally, permeate uses and alternatives may also be considered when studying MBR technologies as this can offset environmental performances from the quality of the wastewater and additional pumping or transportation for disposal or further processing depending on its quality (Holloway et al., 2016).

5.2.2. Scales of Implementation

Future investigation should consider the environmental performance of transitional alternatives for different sizes of communities to identify the optimal extent of each application. Understanding the environmental impacts of various community scales based on density or area may better inform the feasibility of full-scale applications of these technologies. Comparative assessments based on different scales of application have been undertaken using LCA for greywater treatment technologies (Dominguez et al., 2018; Kobayashi et al., 2020), municipal wastewater systems (Tillman et al., 1998), and combined heat and power plants (Guest et al., 2011). Research by Cornejo et al. (2016) has indicated potable water avoided via reuse as the most effective form of resource recovery, especially for increasing scales of application. The results found here indicated both GWP and EUP offsets due to potable water avoidance, however a larger proportion of the impacts observed was through the heat recovery application, which can be further investigated based on different scales of application. Studies on wastewater resource recovery technologies typically focus on chemical or nutrient recovery. Scale comparisons for various capacities, particularly for household (1-2 people served), community (1 500 people served), and city (100 000 people served) scales investigated heat recovery potential integrating water reuse can direct potential innovations for future sustainable water systems, particularly for urban scales. Both environmental and economic savings have already been recognized with these separate systems and recognizing the combined effects of an optimal resource recovery schema is the next step towards addressing rapidly growing global energy and water needs.

5.2.3. Comparisons of Transitional Designs

The framework presented should also be applicable to evaluate the environmental performance of alternative water and district heating innovations for both greenfield and infill developments. Additional options for transitional designs can be assessed based on the needs and available resources for specific regions. As such, demographic, climatic, and water use parameters related to sewage heat recovery and wastewater treatment should be studied. Sewage heat recovery designs have been found to be dictated by sewage properties like flow and temperature, and suitable technologies continue to evolve for full-scale applications (Vestberg, 2017).

6. Conclusion

This thesis guides the reader through current knowledge on the environmental implications of emerging wastewater treatment technologies, elucidating waste-to-resource options that are either presently feasible or are being developed to reduce environmental burdens of conventional sanitation systems. An evaluation of LCA studies for MBR systems was investigated to understand the approaches of evaluating environmental performances of these wastewater treatment technologies. Findings outlined environmental parameters commonly used, focusing on global warming or CO_2 emissions due to the burdens of energy consumption for MBR systems. Offsets in environmental performance may be established through the avoidance of tap water production, which also constitutes considerable energy and chemical requirements. As a result of treating wastewater using MBR for various fit-for-purpose water reuses such as irrigation and toilet flushing, environmental savings may be established. Reporting for heat recovery systems function in the same way in reducing environmental impacts, by avoiding hot water and space heating production from conventional energy mixes that use environmentally intensive sources like fossil fuels, better environmental performances can result from heat recovery systems, particularly where a source like sewage play a dominant role in the infrastructure of modern urban communities.

An assessment of the environmental performance was done for a hypothetical community-based integrated heat recovery and water reuse system. Based on current full-scale applications of sewage heat recovery systems and MBR treatment systems, construction and operational data was collected to create a hypothetical community-based system that is applicable in the Canadian context. While system components vary on a case-by-case scenario, this LCA study provides a snapshot of the environmental benefits of a waste-to-resource schema that currently exists, utilizing municipal sewage that is largely available in conventional municipal systems, with the added benefit of water reuse applications resulting in a reduction of conventional tap water production.

6.1. Major Conclusions

Integrated sewage heat recovery and community-based wastewater treatment offers a realistic means of applying a transitional approach to achieving a circular economy. The ability to harness existing energy from existing trunk sewers to heat a community showed improved environmental performance compared to conventional systems. The main conclusions from the study are:

- Compared to BAU centralized water services, the lowest impacts modeled were for scenarios with community-based MBR wastewater treatment and water reuse.
- Conventional space and water heating components typically contributed the most to GWP values among the system components. A sewage-heat-recovery-based district heating system offered the best environmental performance of the systems modelled.
- Integrating MBR wastewater treatment and water reuse into a district heating schema provides additional environmental savings at a community scale, and under future scenarios utilizing renewable energy mixes.

The framework developed should prove useful for future analyses of other emerging wastewater treatment and resource recovery technologies and can be used to evaluate the environmental performance of the systems used for other regional contexts. Additional data regarding direct operational emissions for such sewer heat recovery systems may be included in future studies to provide a more robust environmental impact analysis.

6.2. Future Work

As full-scale applications of sewage heat recovery systems and wastewater treatment technologies continue to be developed and operated, additional data may be used to adjust the study done here accordingly. Particularly for the Blatchford development in Edmonton, AB, while no water reuse schema is being considered, the full-scale design of sewage heat and geothermal heat recovery for district heating is still expected to be demonstrated. A comparison between the assessment done here and the other real-life applications of the sewage heat recovery system may provide insights on the discrepancies and gaps of the hypothetical study. Further evaluation of environmental impact methods will be important to properly interpret impact findings and the relevance of the results to satisfy the goals and objectives of such assessments, especially as there is no single standard impact method used presently.

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